

Five-hundred-meter **A**perture **S**pherical radio **T**elescope **FAST**



Transient Science with FAST



中国科学院国家天文台
NATIONAL ASTRONOMICAL OBSERVATORIES, CHINESE ACADEMY OF SCIENCES

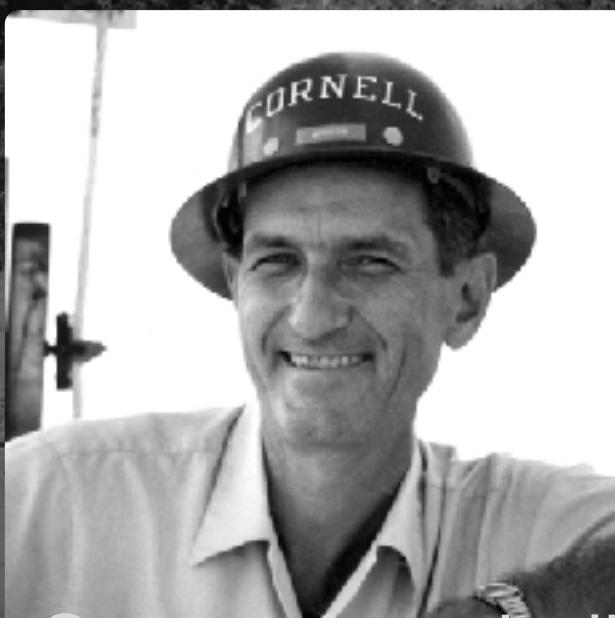
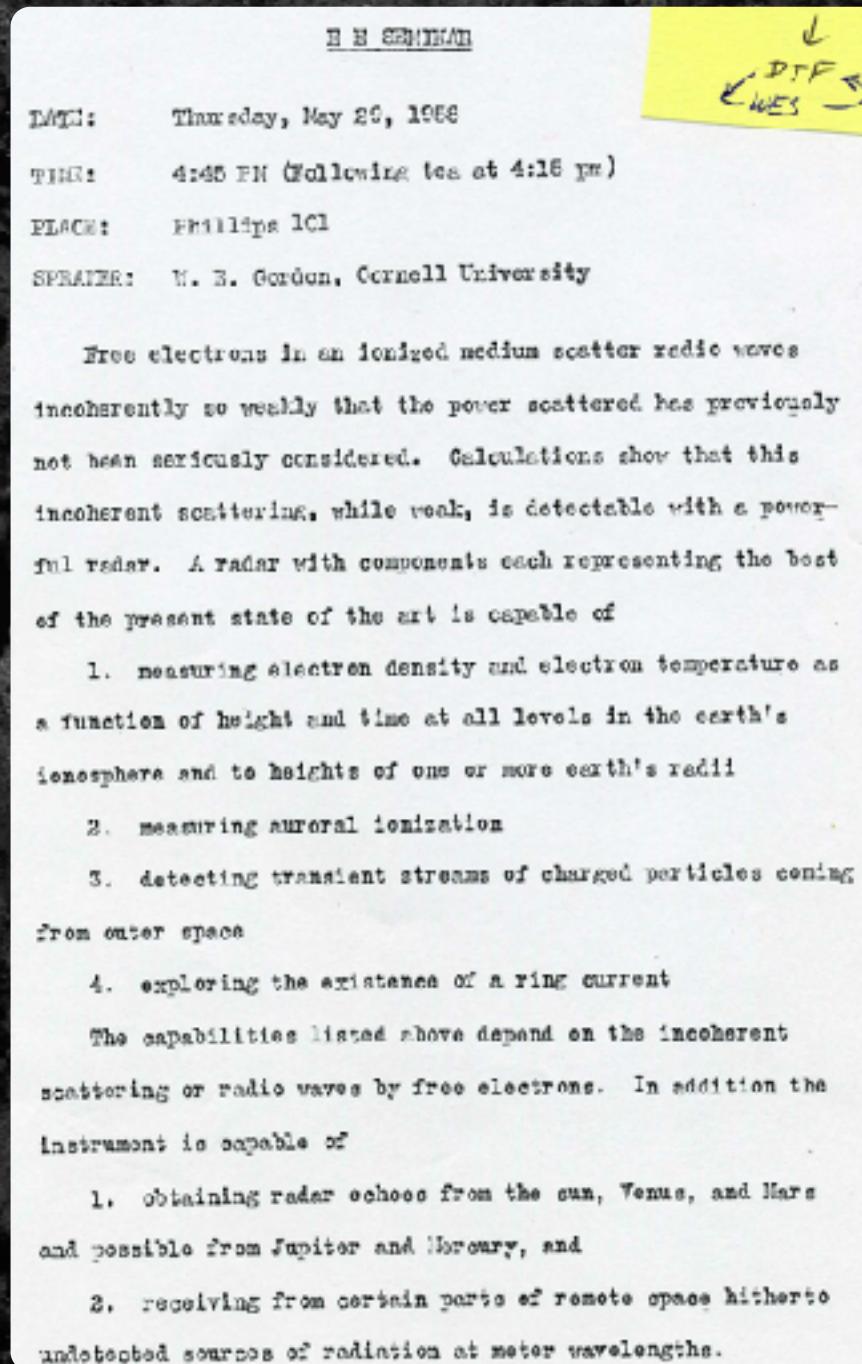

CRAFTS
The Commercial Radio Astronomy FAST Survey
FAST 多科学目标同时扫描巡天

Arecibo
Puerto Rico
(1963-2020)



1958

A 'Beautiful' Mistake



报告人: William E. Gordon

地点: Cornell University EE Dept.

时间: May 29, 1958

Electron

Ion

Scatter from individual electrons
=> Echo bandwidth of 100s of kHz=> need **300 m!**

Ken Bowles (NIST)
– bandwidth reflected ion velocities not electron velocities.

Gordon: 1958 URSI meeting

need only **30m** But

ARPA-(Advanced Research Projects Agency)

decided to sponsor a super-dish!



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1996



R.D. Nan

Y.H. Qiu

SHOT ON MI 9
PHOTO BY QIU

●OOO

FAST

Guizhou, China

2020-now



1996 proposed
2007 funded

2020 formal operation commenced

>500 new pulsars; >120 papers, including, 5 Nature, 1 Science, 2 Nat. Astro.

Observables

- a) HI 21cm (imaging & galaxies)
- b) Pulsars (FRBs)
- c) Molecular Spectroscopy
- d) VLBI
- e) SETI

NO large-scale survey has simultaneously observed HI and pulsar. Why?

continuous coverage
70 MHz ~ 3 GHz

Review

International Journal of Modern Physics D
Vol. 20, No. 6 (2011) 989–1024
© World Scientific Publishing Company
DOI: 10.1142/S0218271811019335



THE FIVE-HUNDRED-METER APERTURE SPHERICAL RADIO TELESCOPE (FAST) PROJECT

RENDONG NAN^{*†§}, DI LI^{*‡¶}, CHENJIN JIN^{*}, QIMING WANG^{*},
LICHUN ZHU^{*}, WENBAI ZHU^{*}, HAIYAN ZHANG^{*†},
YOULING YUE^{*} and LEI QIAN^{*}

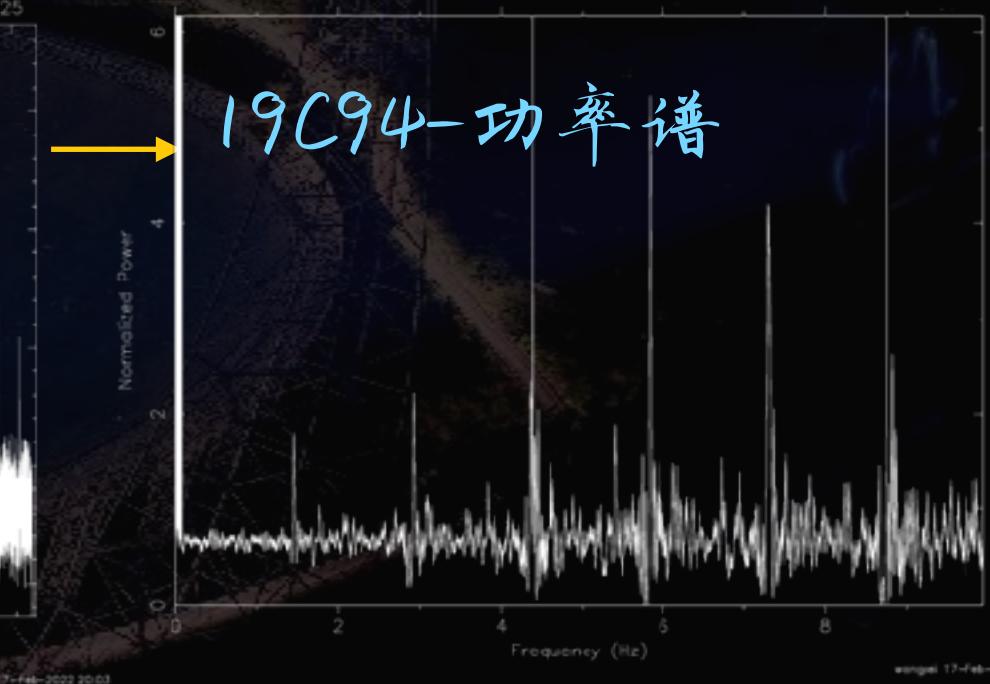
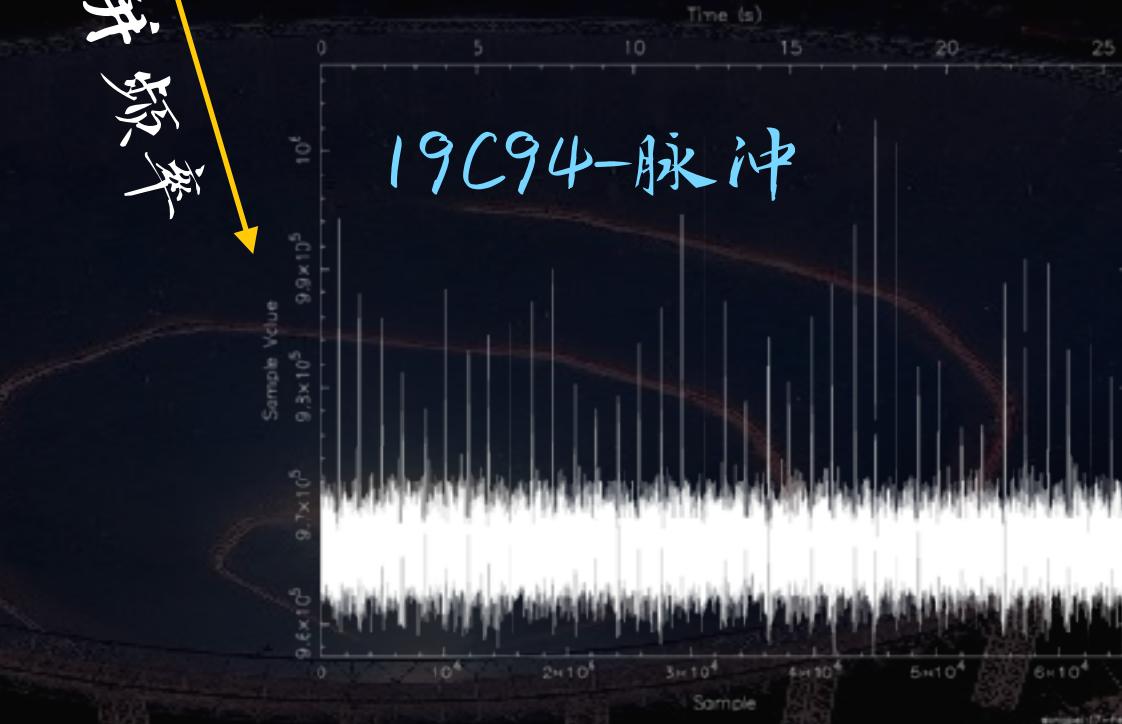
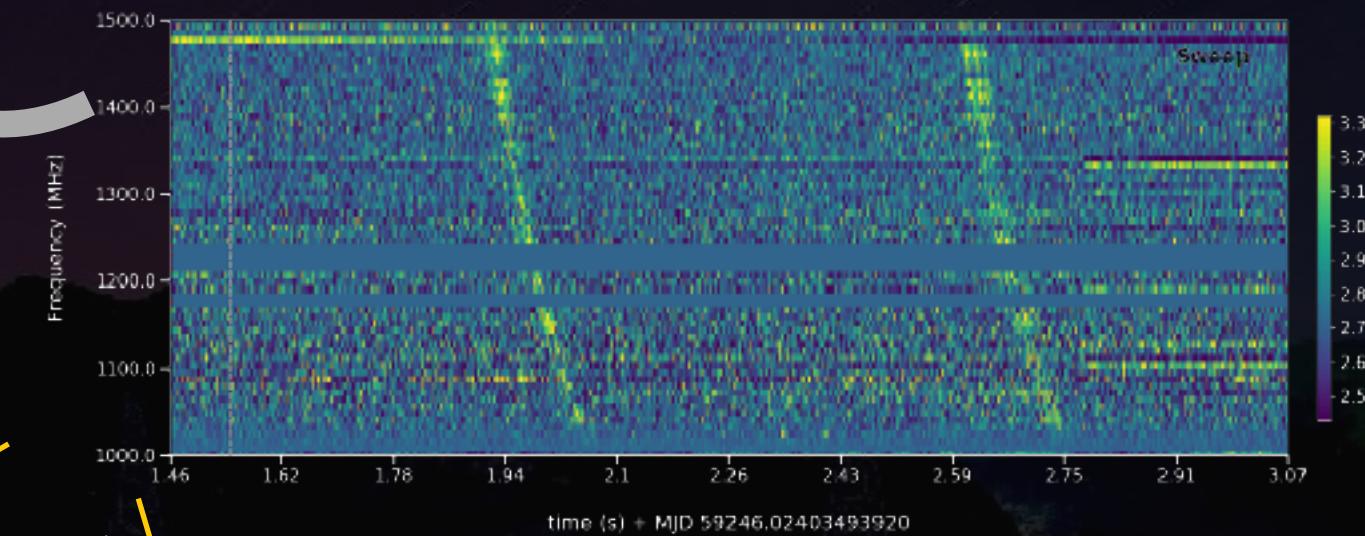
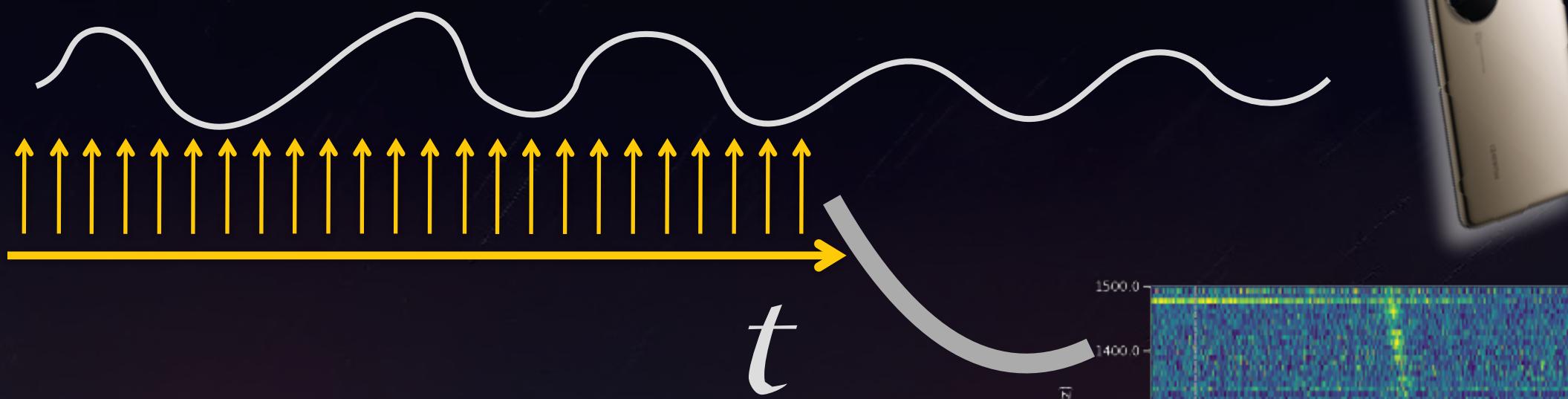
Nan, Li, Jin et al. 2011, IJMR-D, 20, 989
(>500 google scholar citations)

Li & Pan, 2016, Radio Science, 51, 7
Li et al. 2018, IEEE Microwave, Vol. 19, Issue 3

射电信号采集

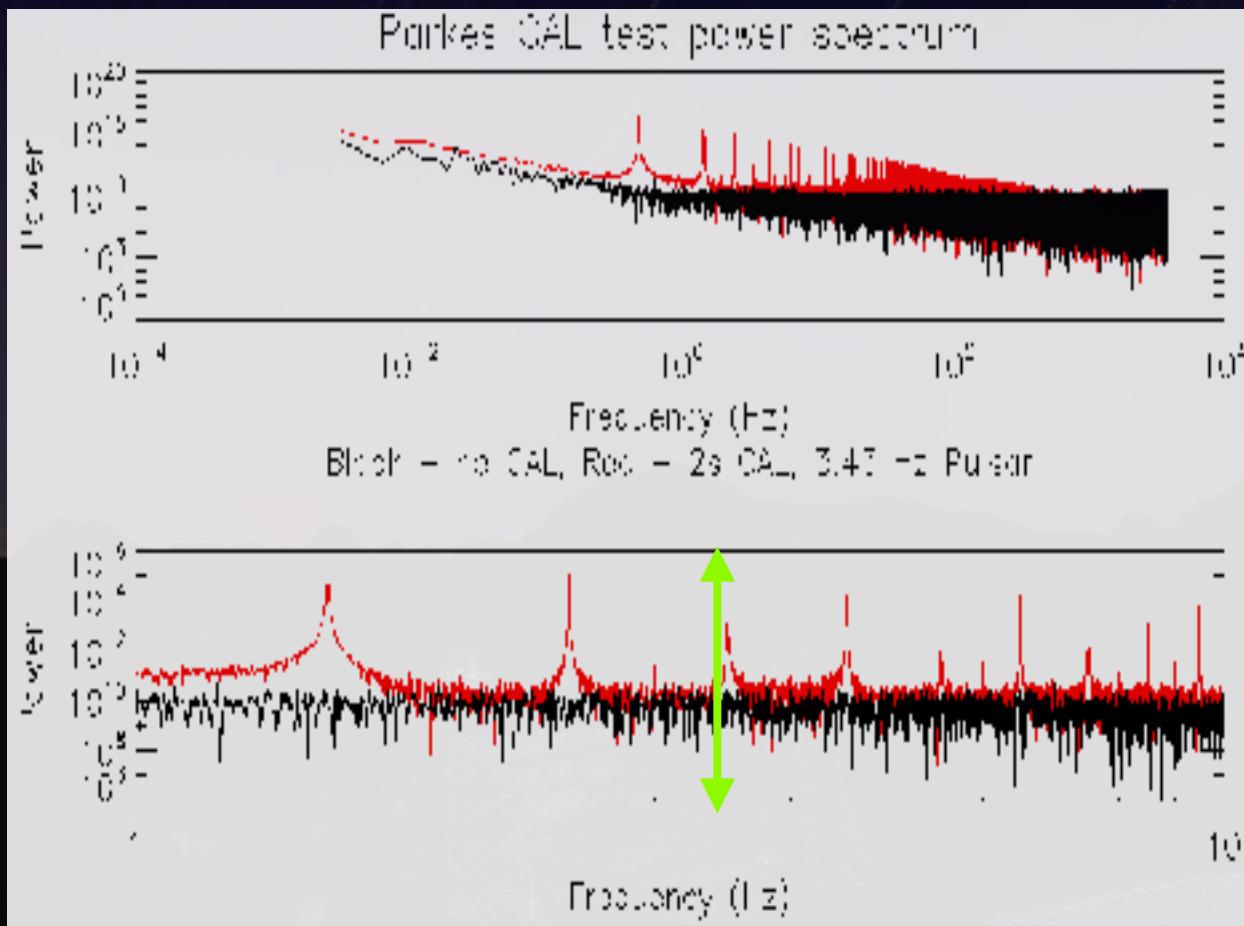


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Breakthrough

- HI/pulsar commensality!



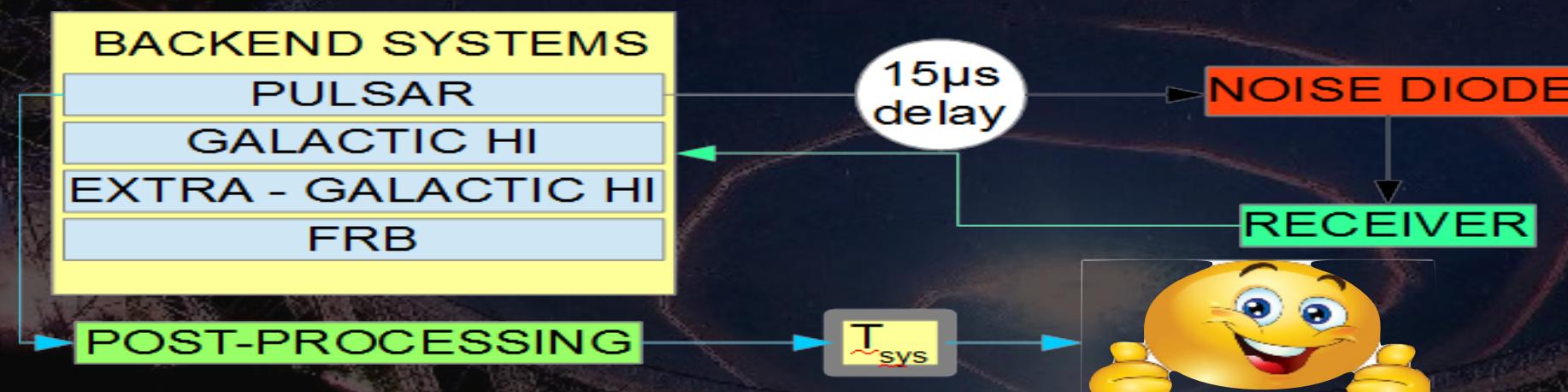
High Cadence CAL

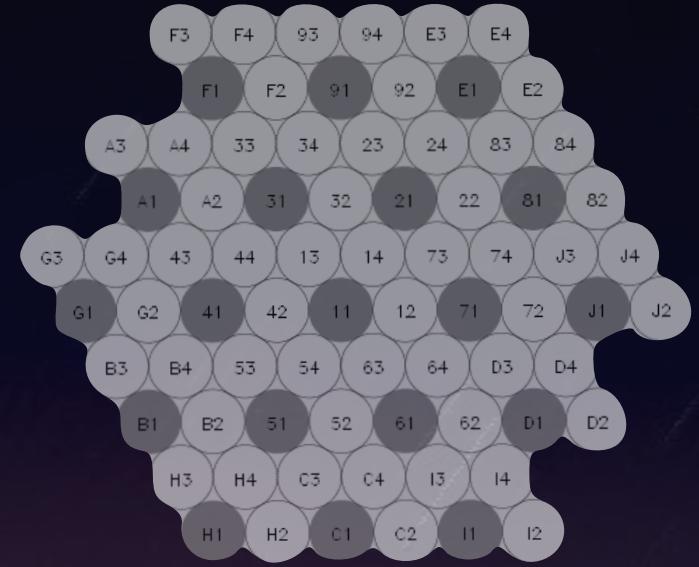
- Run a “winking” CAL at the pulsar backend sampling rate ($\sim 100 \mu\text{s}$)
- Pulsar backend trigger automatic CAL
- post-processing of pulsar data recovers T_{sys}
- CAL timing information to be shared with all groups.

PATENT APPLICATION:
A HIGH FREQUENCY WHITE NOISE INJECTION SYSTEM

by Marko Krčo¹, Yan Zhu¹, Richard N. Manchester², Chenjin Jin¹, Alex Dunning³, George Hobbs², Ryan Lynch³, Di Li¹, Felix J. Lockman³, William Coles⁴, Jim Cordes⁵, Jimi Green², Carl Heiles⁶, Mengting Liu¹, Naomi M. McClure-Griffiths⁷, Zhichen Pan¹, Lister Staveley-Smith², Ningyu Tang¹, Zhu Weiwei¹, Youling Yue¹, Kai Zhang¹

Krčo et al.
patent pending





Commensal Radio Astronomy FAsT Survey

Li et al. 2018

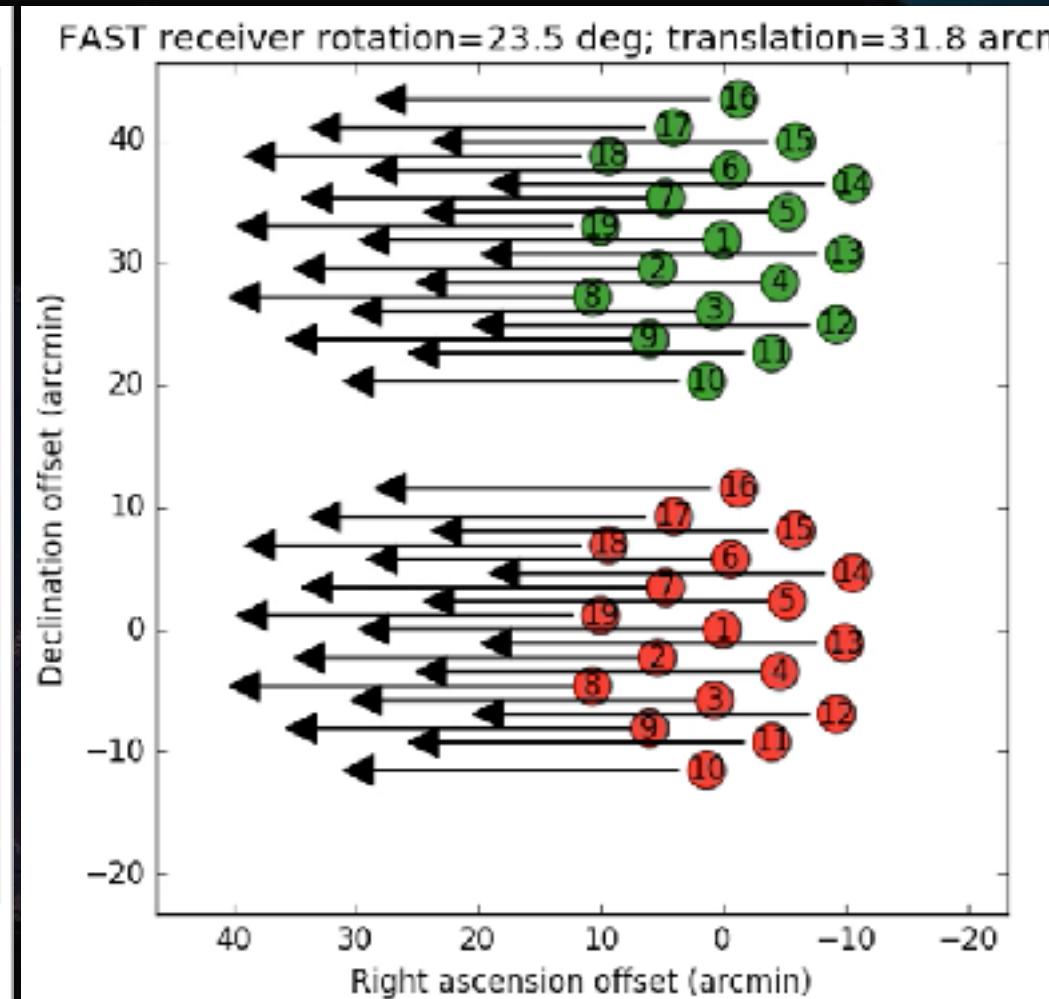
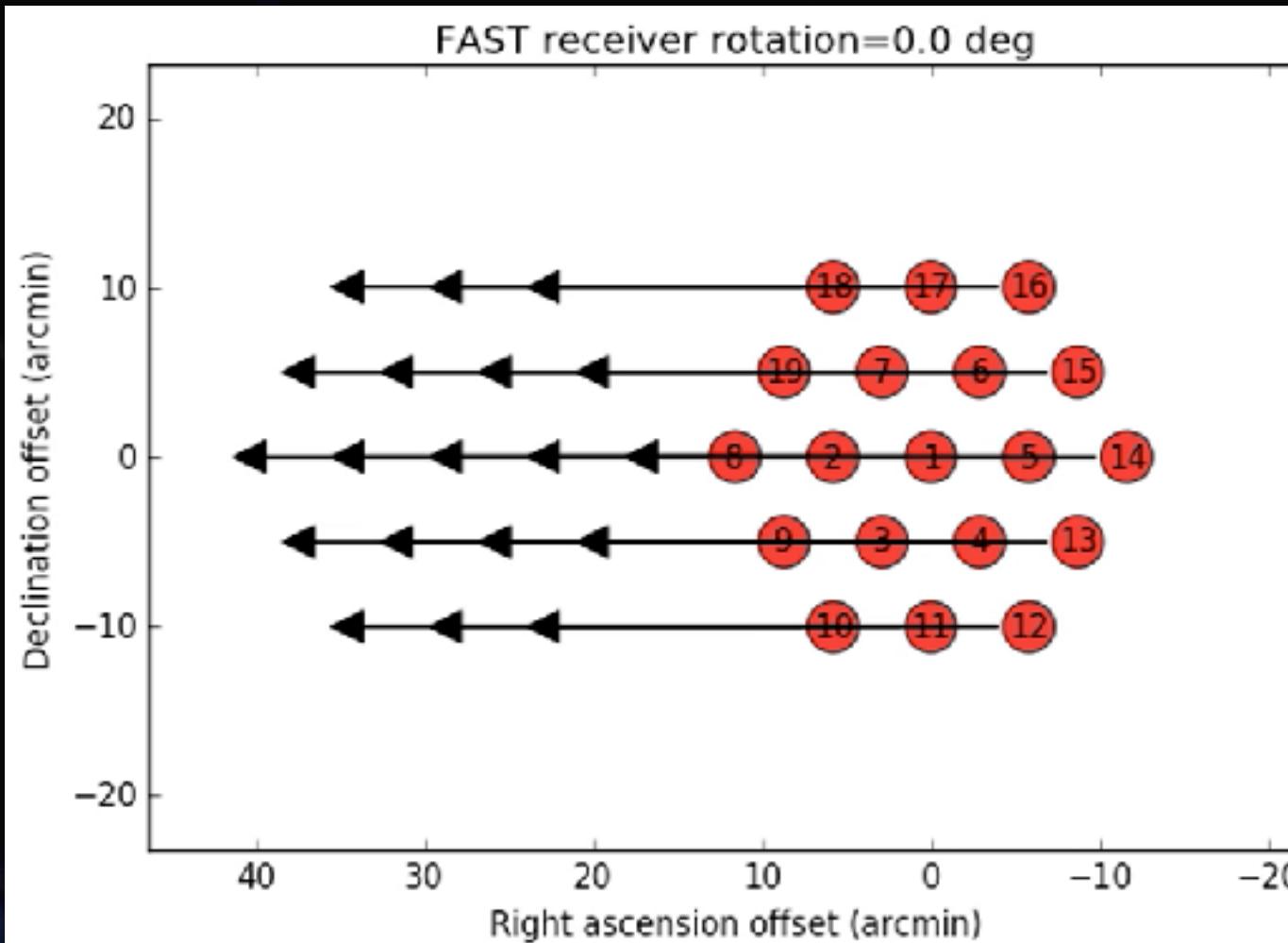
IEEE Microwave, Vol 19, Issue 3, p112



220 full days

5280 hours

Drift (sidereal)



2018/5/24

Commensal Radio Astronomy FAST Survey



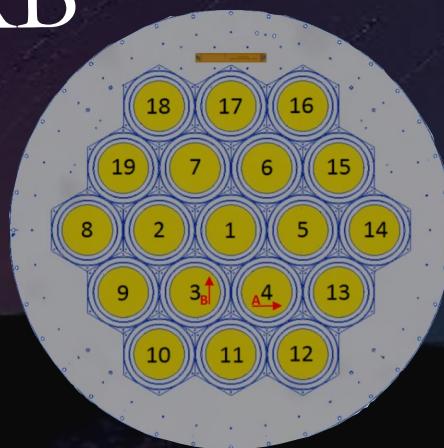
unprecedented commensality
pulsar, galaxy, imaging, and FRB

FAST 'big data' stream

pulsar: $19 \times 8\text{bit} \times 4 \times 4\text{k} \times 2 \times 10^4$ per second

HI: $19 \times 8\text{bit} \times 4 \times 1\text{M} \times 2 / \text{s}$

- 6 GB/s
- 25TB/h
- 550TB/day
- 10 PB/ year



Di Li, Pei Wang, Lei Qian, Marko Krcic, Alex Dunning,
Peng Jiang, Youling Yue, Chenjin Jin, Yan Zhu,
Zhichen Pan, and Rendong Nan

Having achieved "that light" immediately prior to the ceremony introducing it on 25 September 2016, China's 500-m aperture spherical radio telescope (FAST) is now being kept busy with observations. Its innovative design requires

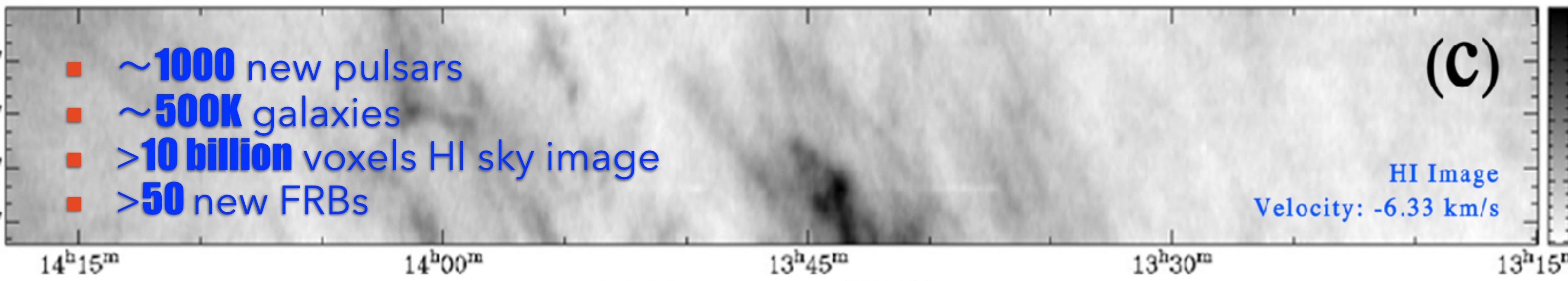
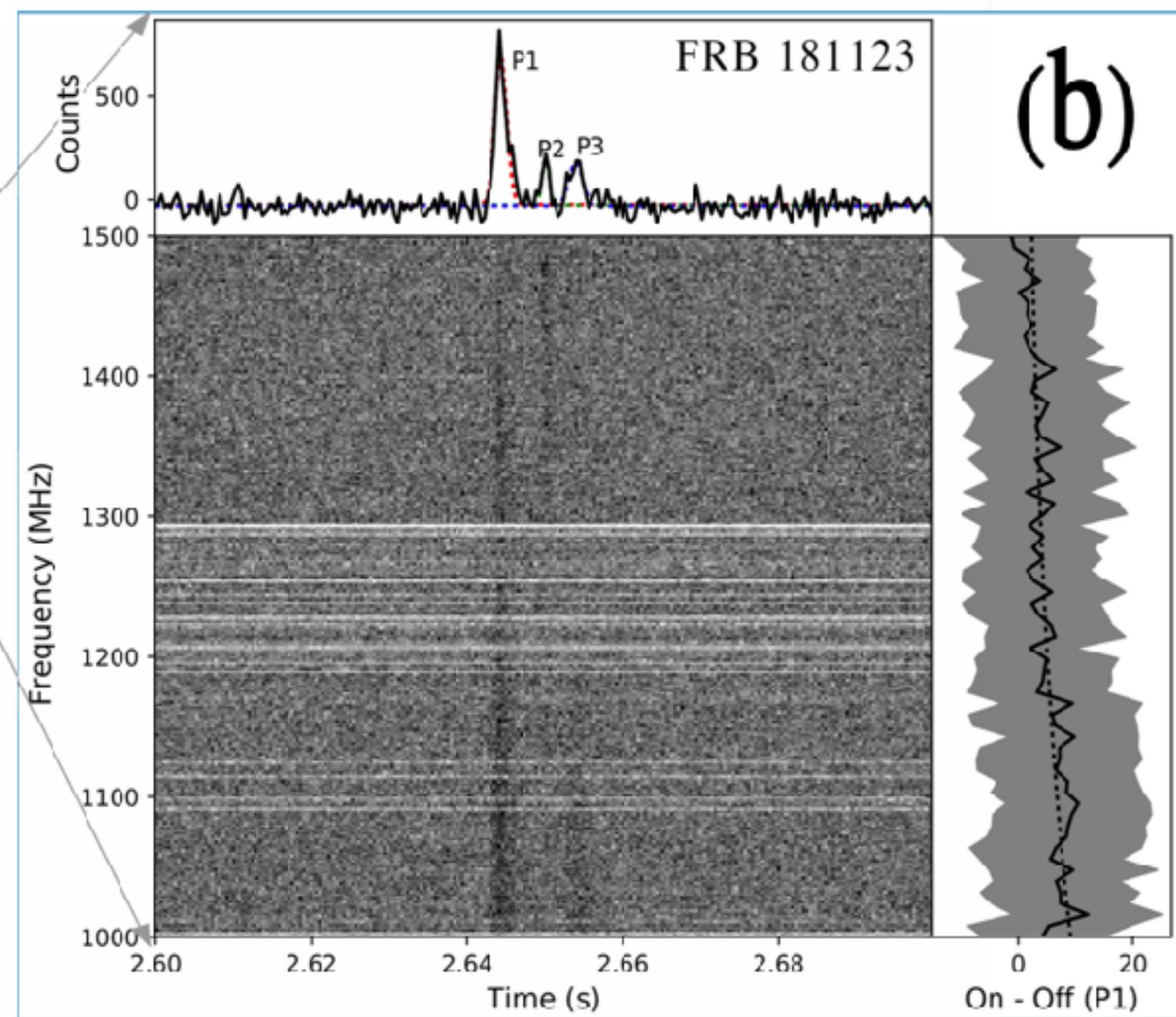
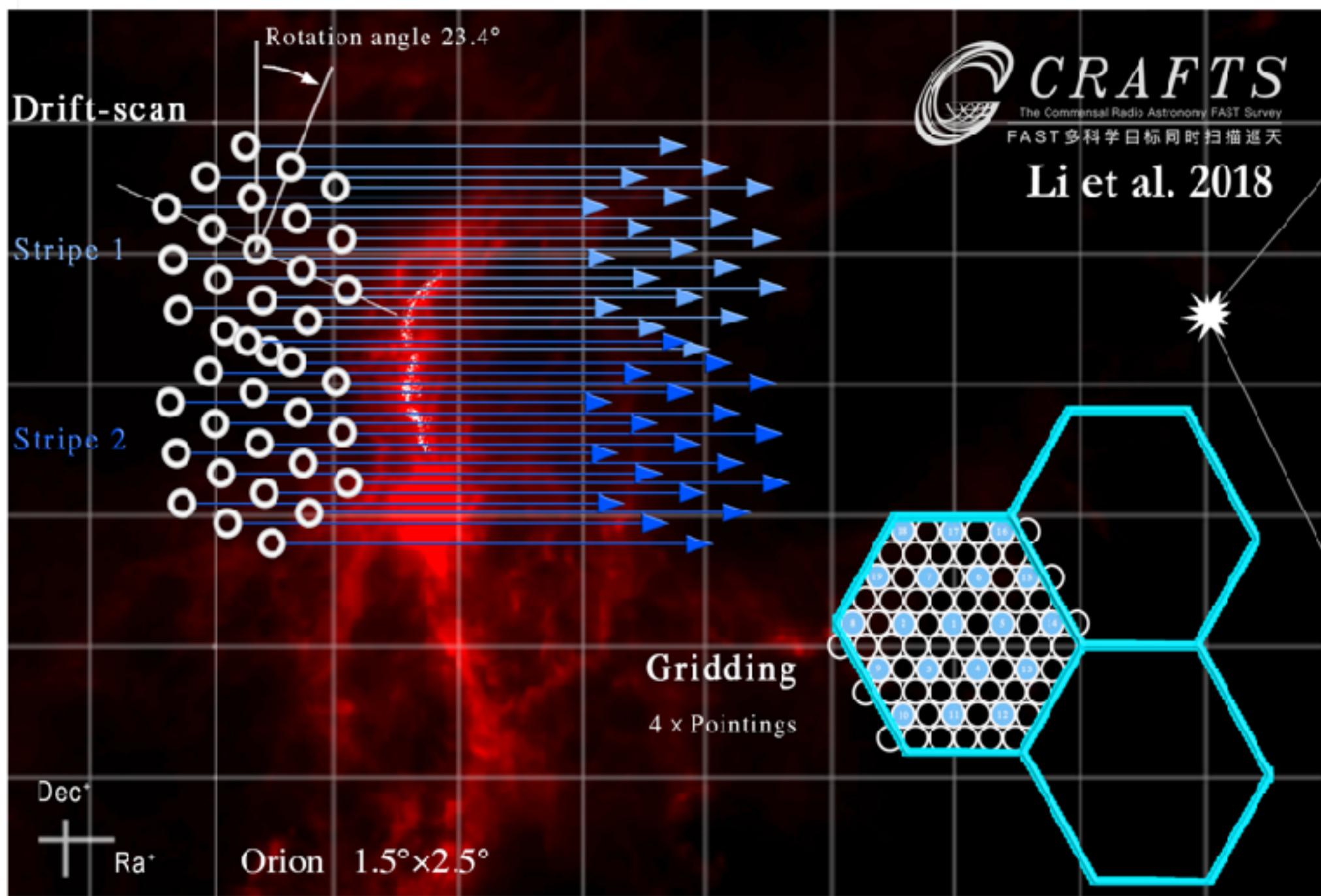
ALU points to be measured and driven instead of just the two axes of motion, e.g., azimuth and elevation for most conventional antennas, to realize pointing and tracking. We have drafted a survey plan to exploit the full sensitivity of FAST, while acknowledging the complexities involved during system operation.

Li et al. 2018, Invited Review
IEEE Microwave, Vol 19, Issue 3, p112

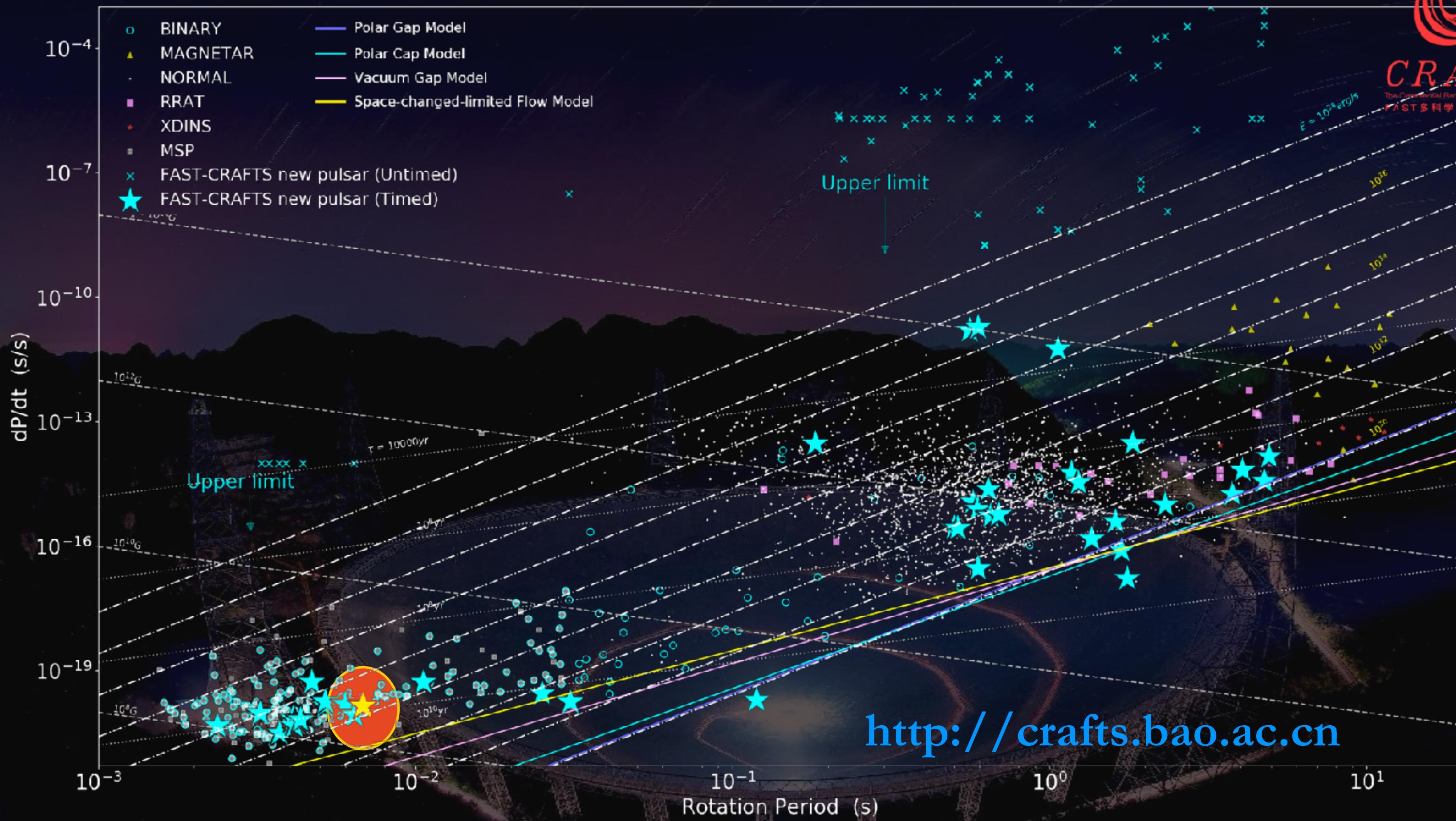


The Commensal Radio Astronomy FAST Survey

FAST 多科学目标同时扫描巡天



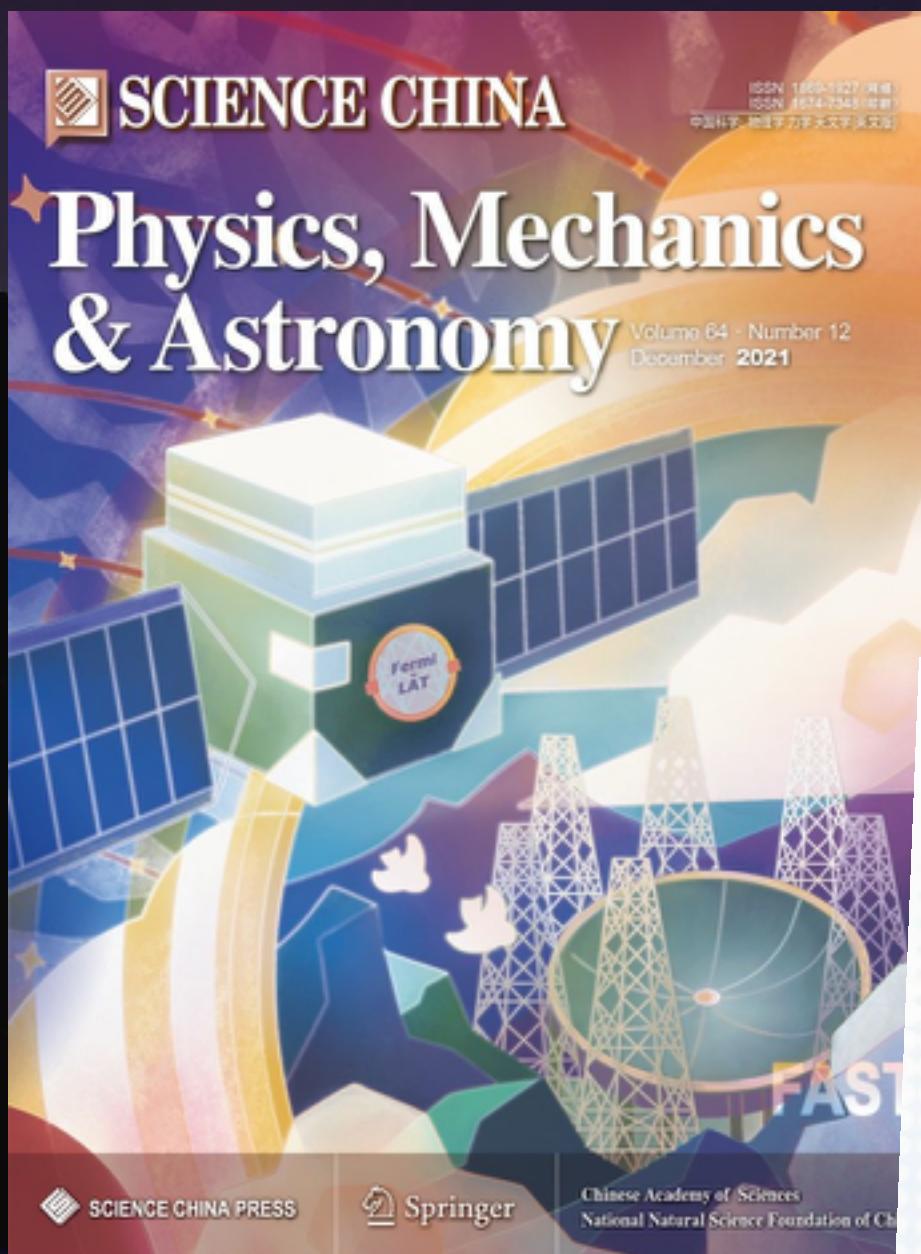
CRAFTS new pulsars >160, 41MSP, 1 DNS



<http://crafts.bao.ac.cn>

FAST's first Milli-Second Pulsar (MSP)

开启FAST与国际多波段设备合作
系统发现脉冲星与辐射机制研究的新途径



Dr. G. Hobbs, a member of the Gravitational Wave International Committee (GWIC):

"a significant discovery, showing the potential of FAST for contributing to GW detection..."

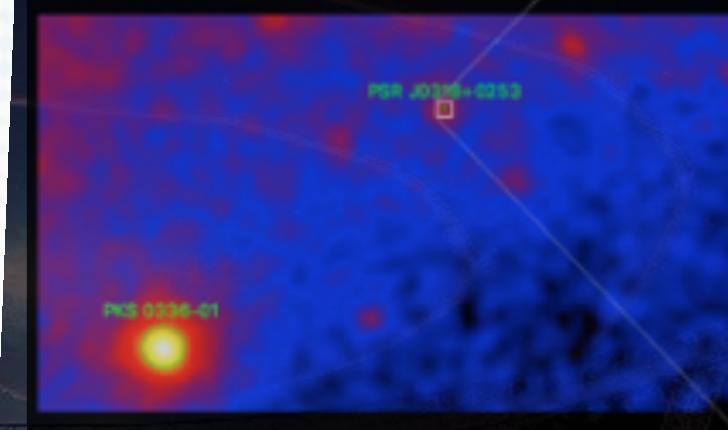


PSR J0318+0253

The Firs

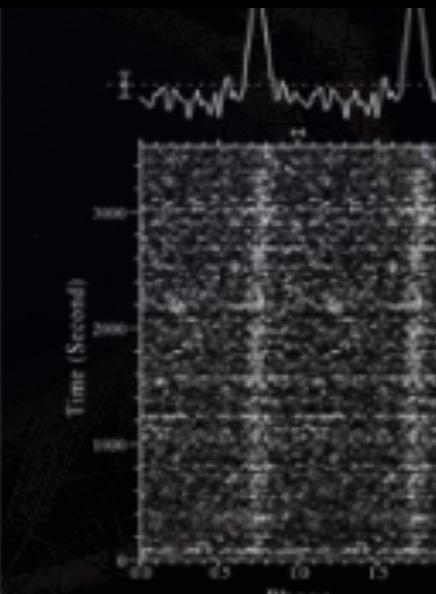


Pei Wang / Di Li @ NAOC

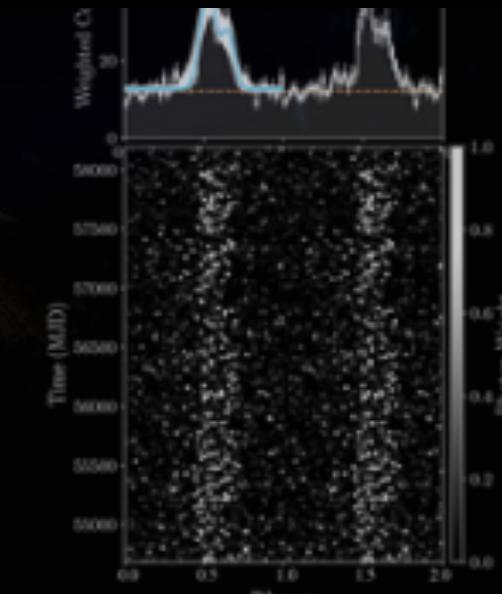


A New MSP toward the Fermi-LAT unassociated source 3FGL J0318.1+0252

a) FAST



b) Fermi-LAT



FAST & Fermi-LAT MoU, 2017.12

Memorandum of Understanding between

The FAST Collaboration
and

The Fermi Large Area Telescope (LAT) Collaboration
for
Pulsar Studies using the FAST Radio Telescope and
the Fermi Large Area Telescope

For the FAST
organization

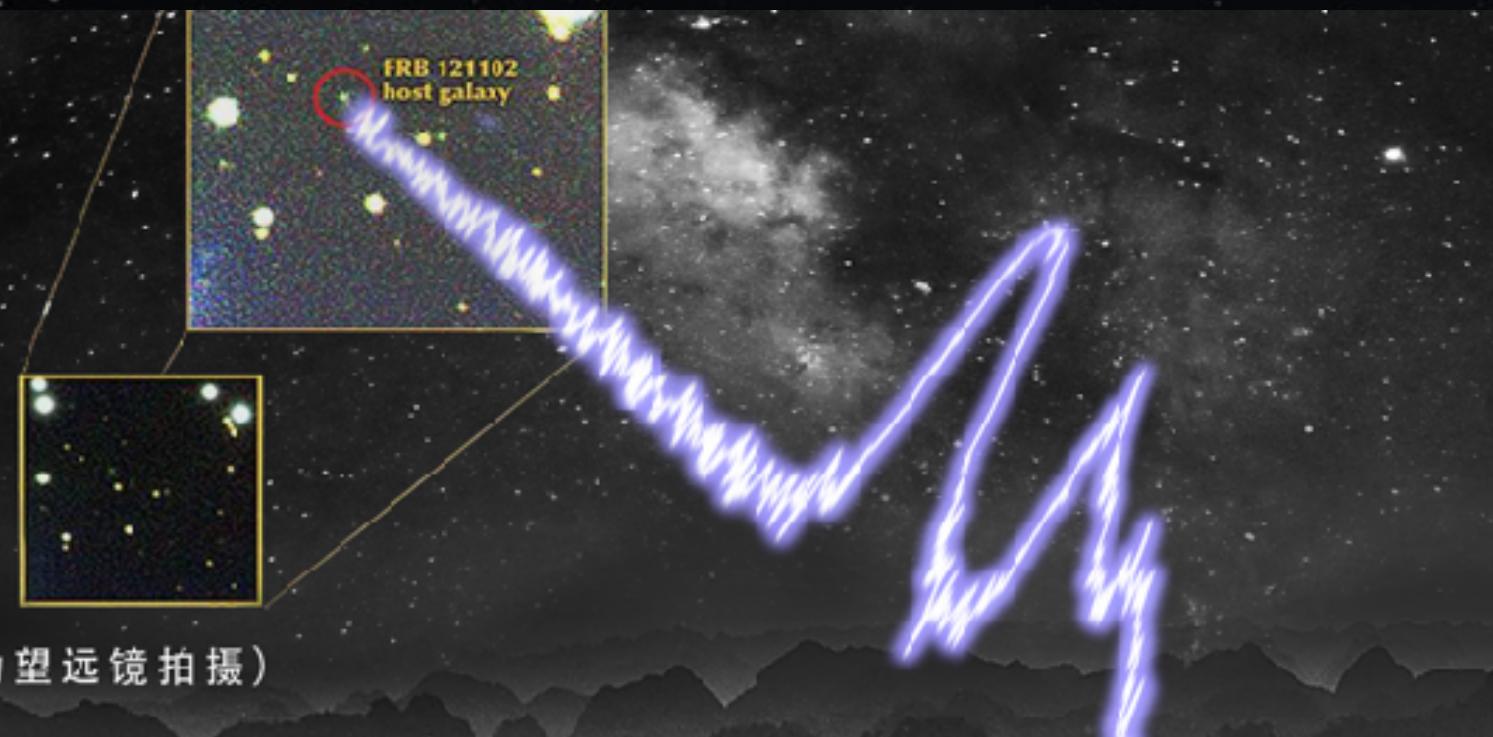
Jun Yan Dec. 19, 2017

For the Fermi LAT collaboration: Professor Peter F Michelson, Principal Investigator

Peter F Michelson Dec 14, 2017

Hard copies of this document are for REFERENCE ONLY and should not be
considered the latest revision.

宿主矮星系

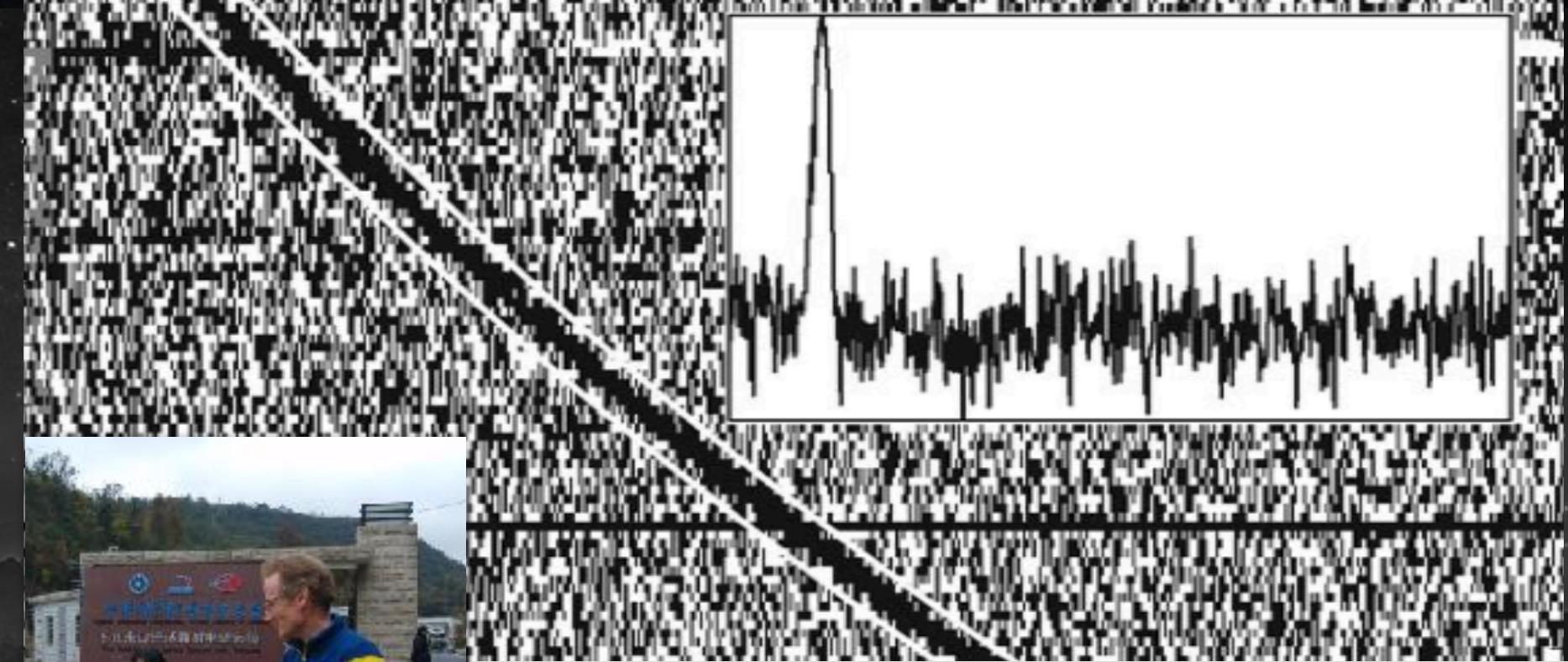


(哈勃望远镜拍摄)

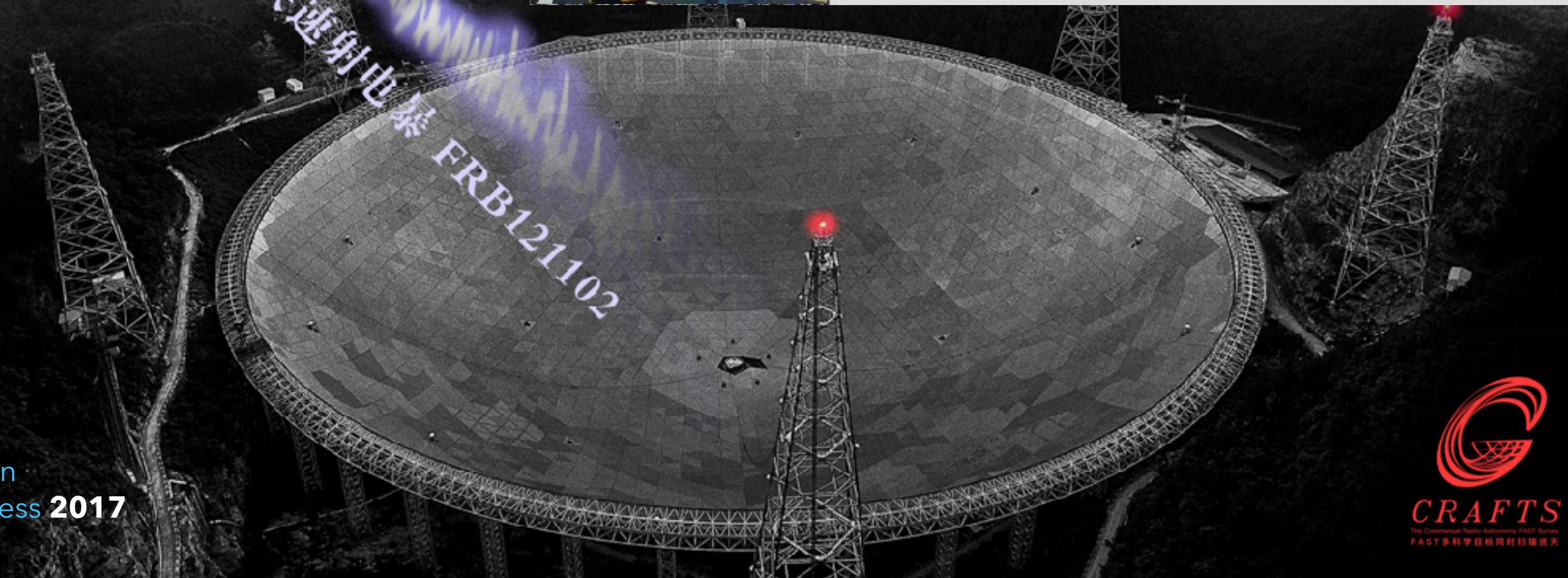


FRB 121102 对应星系

"The most important discovery in astronomy since LIGO" –AAS Press 2017



The 'Lorimer' bursts



[Contents](#) [hide]

- 1 Welcome to the FRB Theory Wiki!
- 2 Contributing to the Wiki
 - 2.1 Rules and Guidelines
- 3 Summary Table

> 50 categories of models
No clear consensus

Welcome to the FRB Theory Wiki!

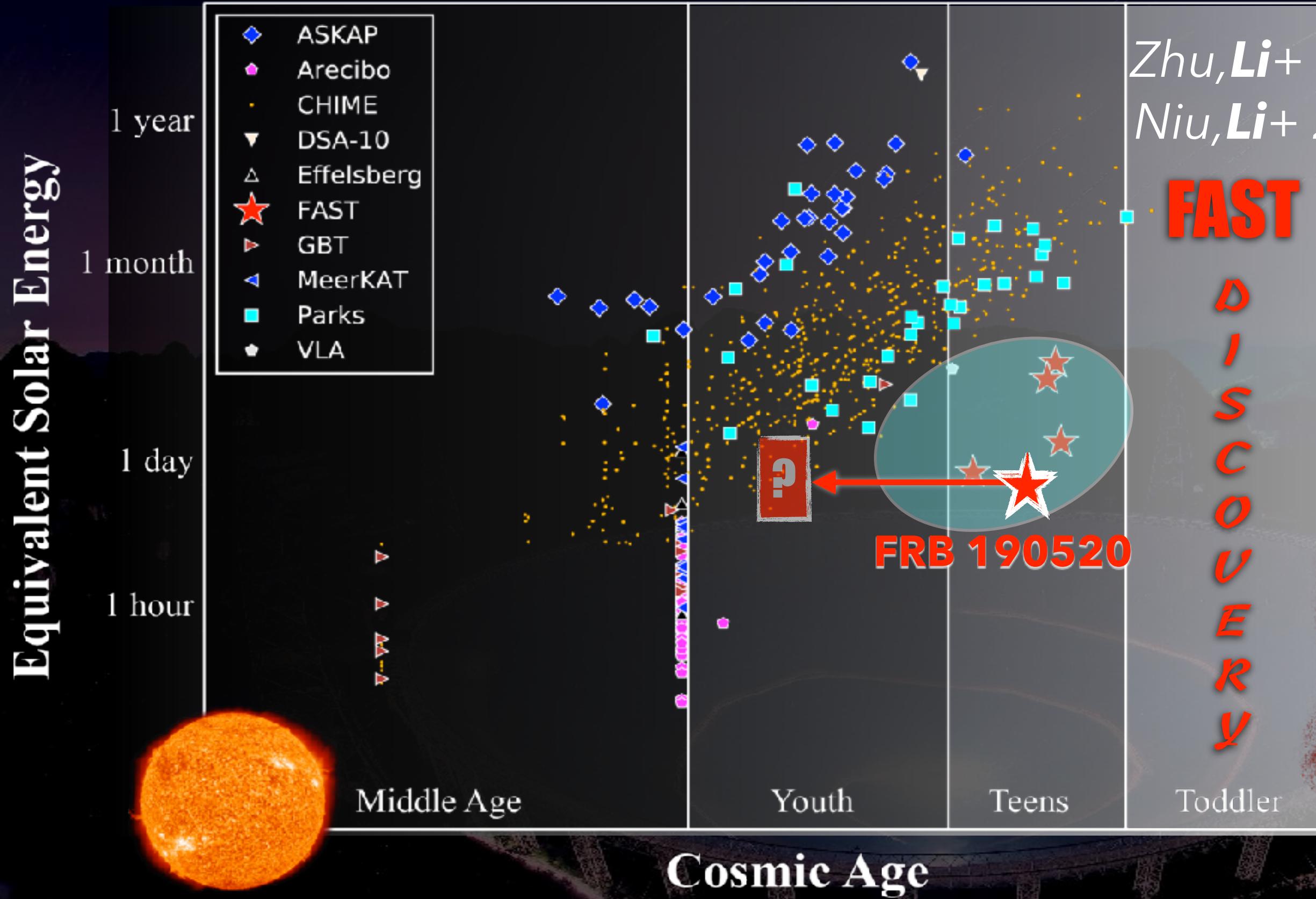
Name	Category	Progenitor	Type	Energy Mechanism	Emission Mechanism	LF Radio Counterpart	HF Radio Counterpart	Microwave Counterpart	THz Counterpart	OIR Counterpart	X ray Counterpart	Gamma ray Counterpart	GW Counterpart
NS-WD Accretion	Accretion	NS-WD	Repeat	Mag. reconnection	Curv.	Yes	--	--	--	--	--	Yes, but unlikely detectable	--
AGN-KBH	AGN	AGN-KBH Interaction	Repeat	Maser	Synch.	Yes	--	--	--	Supernova	--	Yes	Yes
AGN-SS	AGN	AGN-Strange Star Interaction	Repeat	Electron oscillation	--	Yes	--	--	--	Thermal	--	Yes	Yes
Jet-Caviton	AGN	Jet-Caviton Interaction	Both	Electron scattering	Bremsst.	Yes	Yes	--	--	--	--	Possible GRB	Yes
Wandering Beam	AGN	Wandering Beam	Repeat	--	Synch.	Yes	--	--	--	--	Yes	--	--
NS to BH (DM-Induced)	Collapse	NS to BH	Single	Mag. reconnection	Curv.	Yes	--	--	--	--	--	--	Yes
NS to KNBH	Collapse	NS to KNBH	Single	Mag. reconnection	Curv.	Yes	--	--	--	--	Possible afterglow	Possible GRB	Yes
NS to Quark Star	Collapse	NS to Quark Star	Single	β -decay	Synch.	Yes	--	--	--	--	Yes	Yes	Yes
SS Crust	Collapse	Strange Star Crust	Single	Mag. reconnection	Curv.	Yes	--	--	--	--	--	--	Yes
Axion Cloud and BH	Collision / Interaction	Superradiant Axion Cloud and BH	Repeat	Laser	Synch.	Yes	--	--	--	--	--	--	Yes



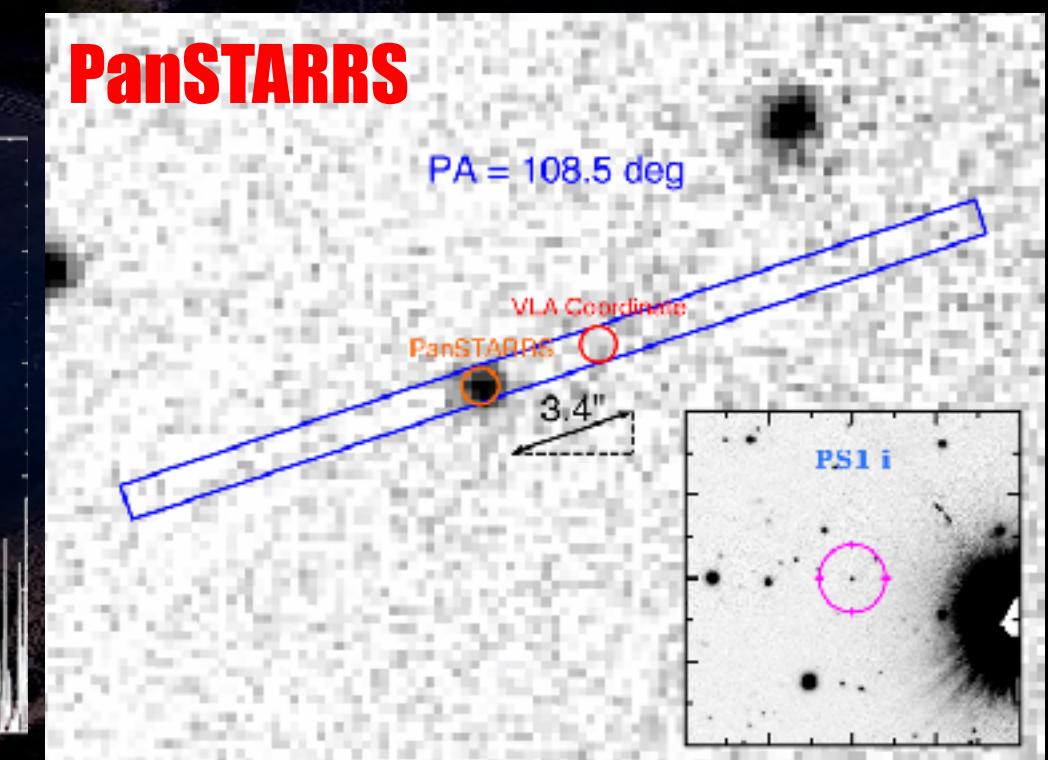
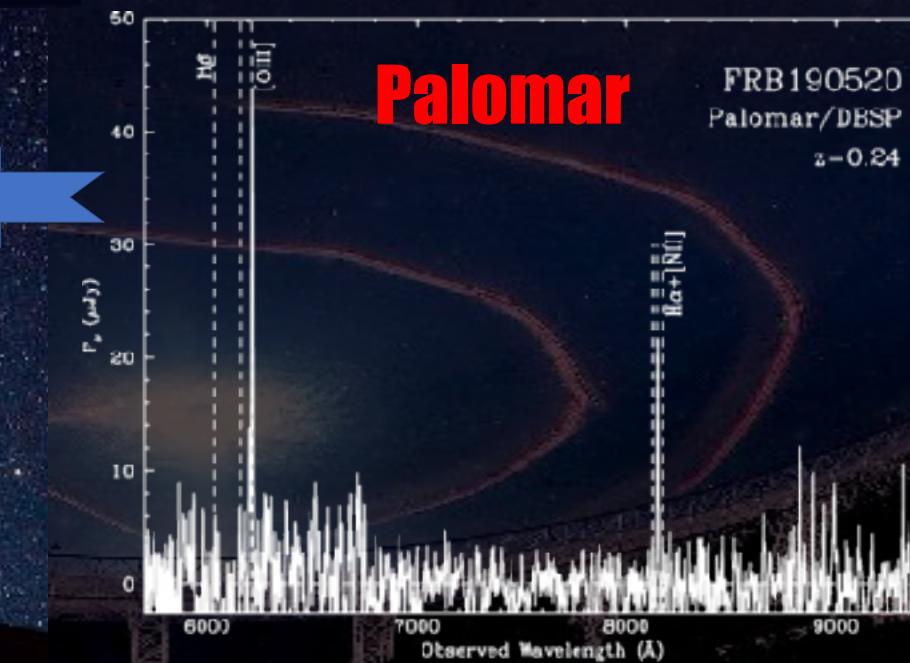
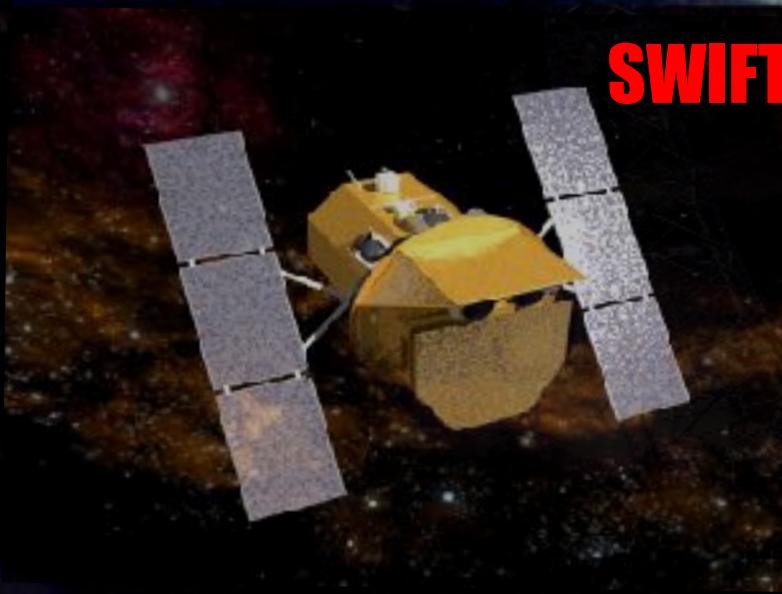
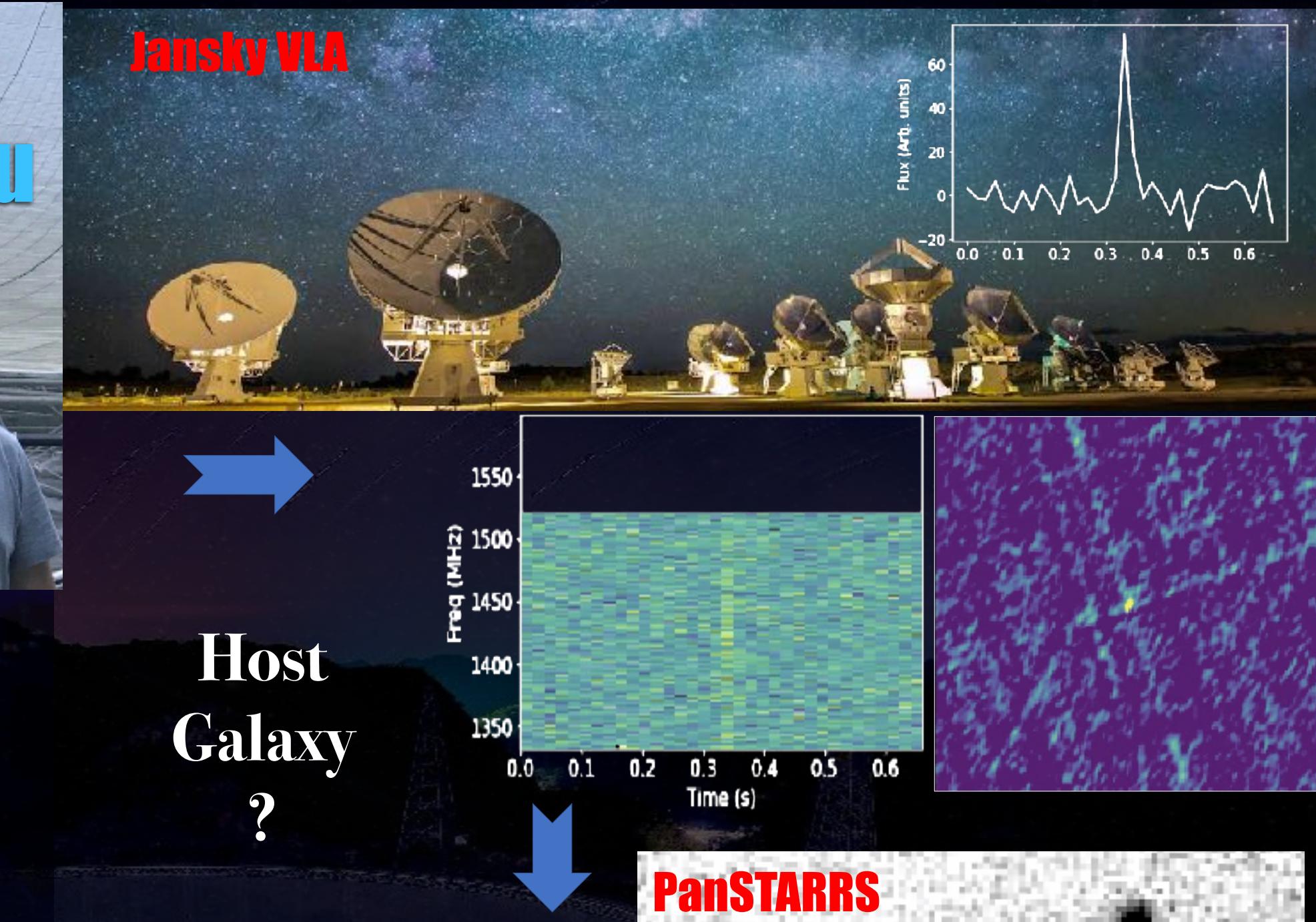
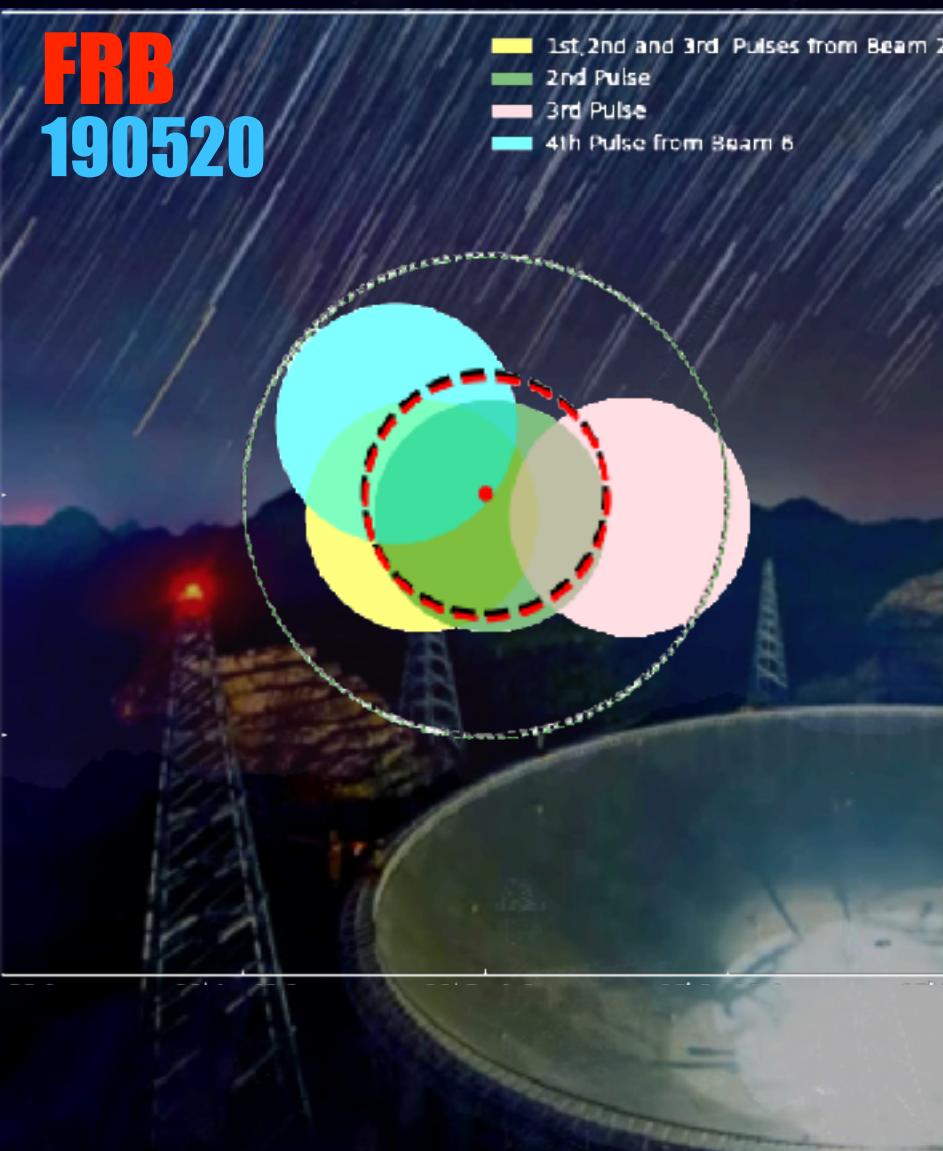
CRAFTS
The Communal Radio Astronomy FAST Survey
FAST多科学日标同时扫描巡天

C
R
A
F
T
S

CRAFTS reveals a high event rate >100K per day!



Big Bang

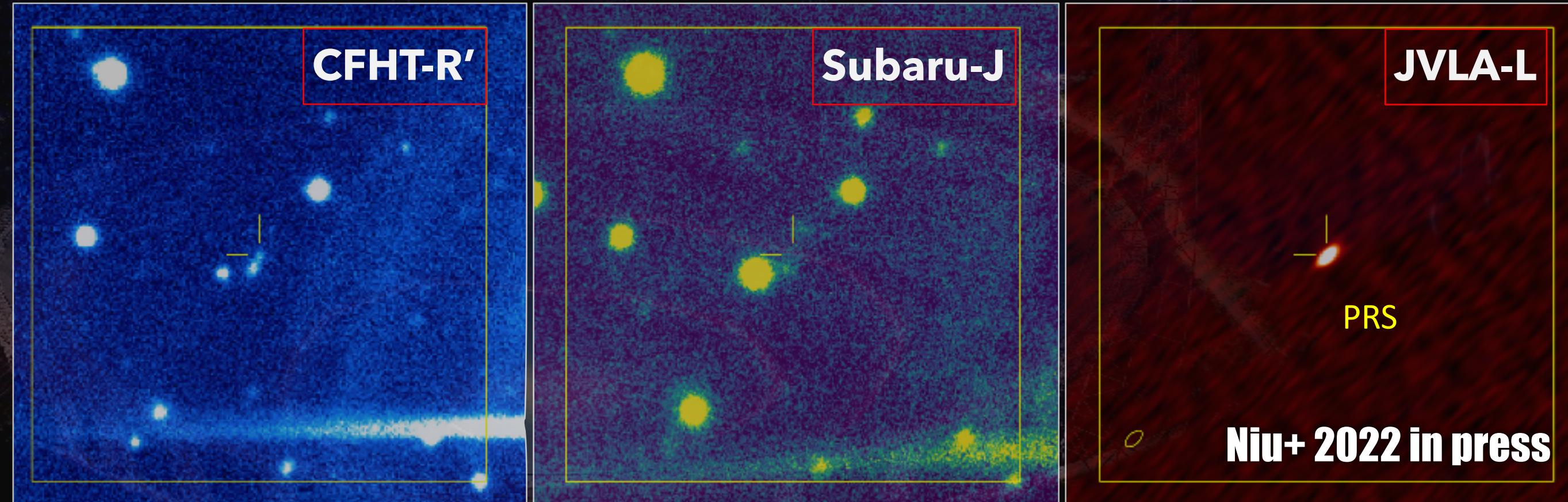


Host Galaxy Identification

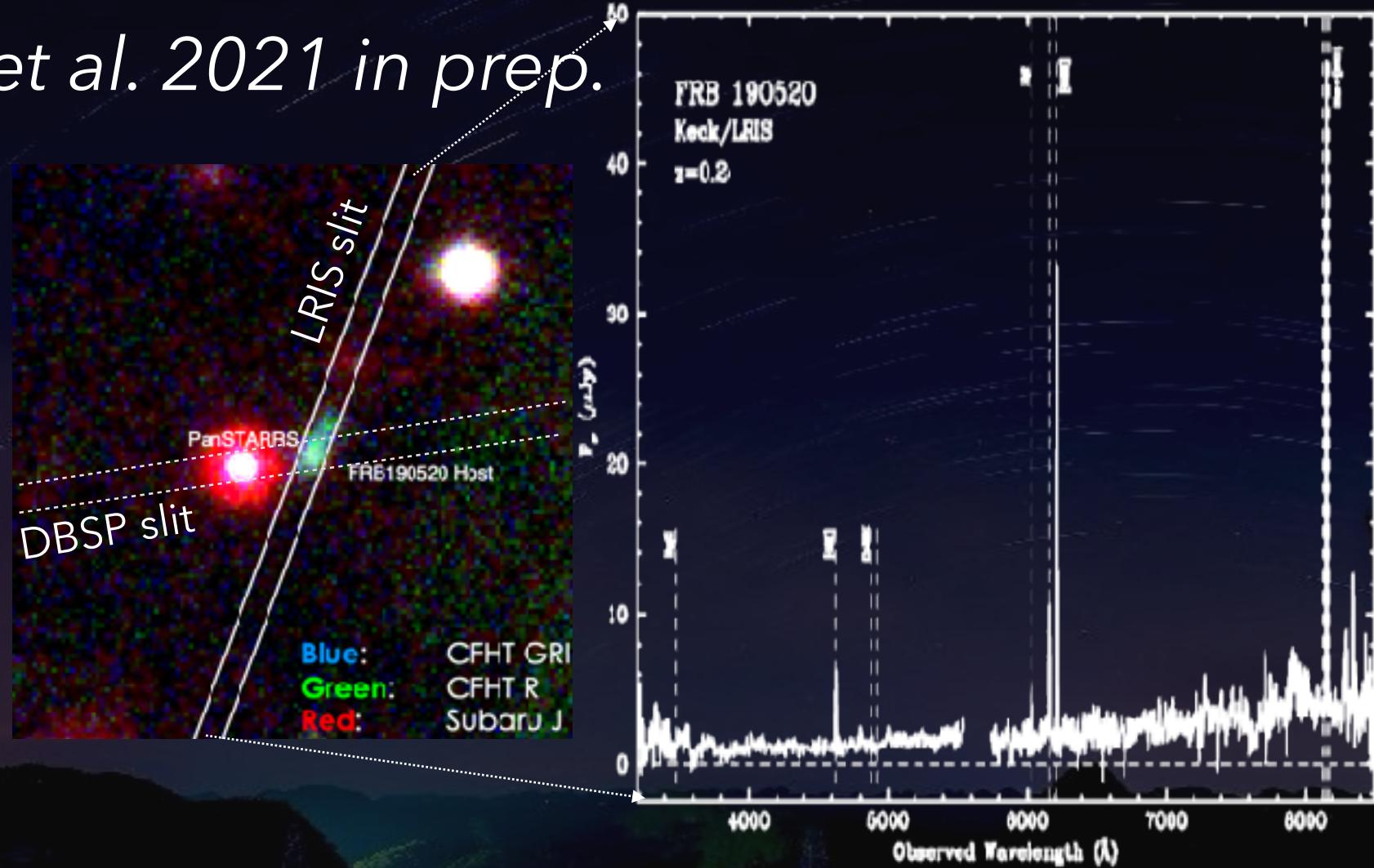
Tsai et al. 2021 in prep.

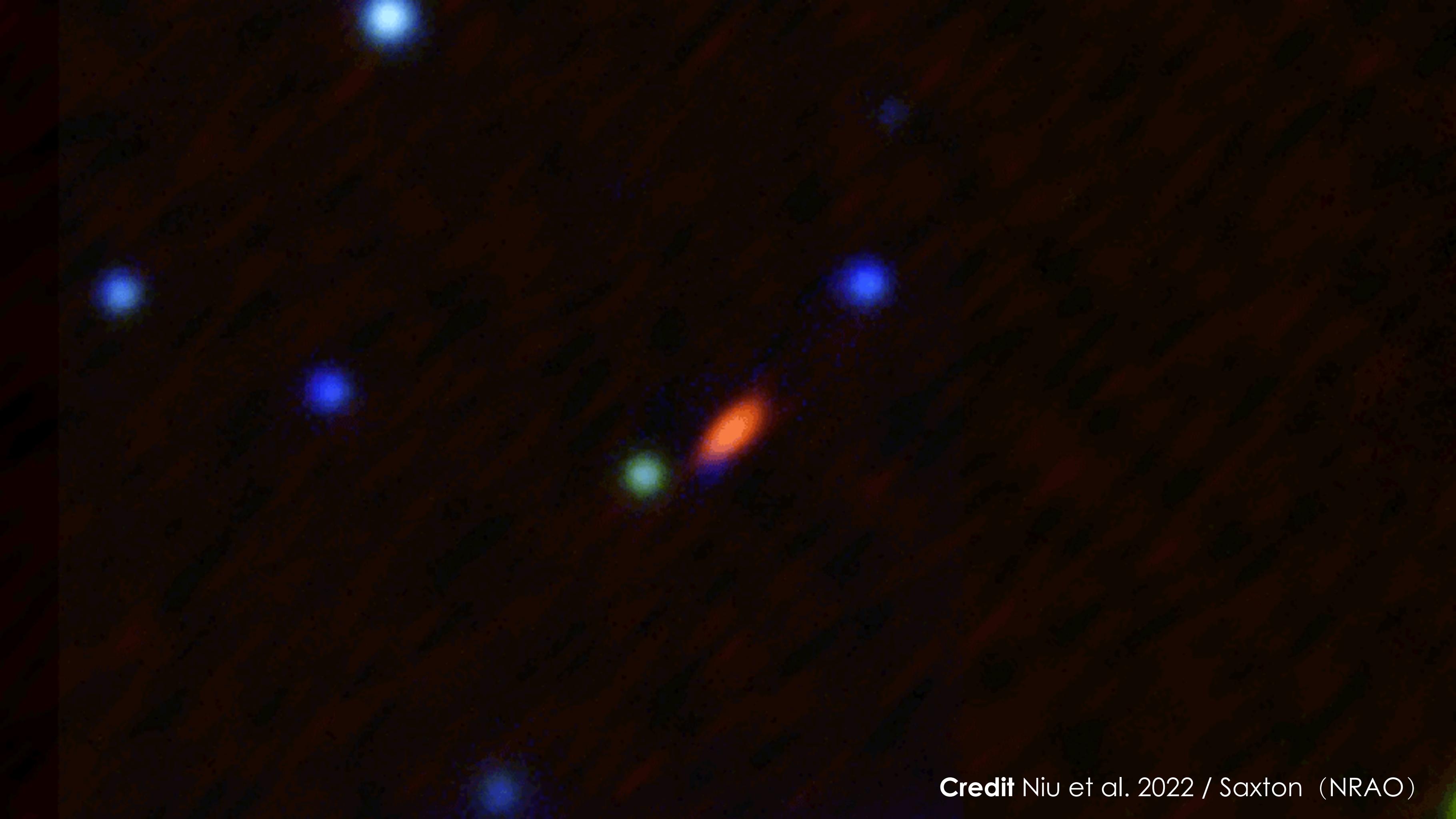
- Optical R'-band (CFHT MegaCam)
5427Å-7041 Å: H_{β} 4861Å, [OIII] 4959Å, and [OIII] 5007Å
- Infrared J-band image (Subaru/MOIRCS)
- Keck LRIS +
Palomar DBSP

Redshift
 $z=0.241$
 \ll
 $Z(DM_{\text{excess}}) \sim 1$



Niu+ 2022 in press



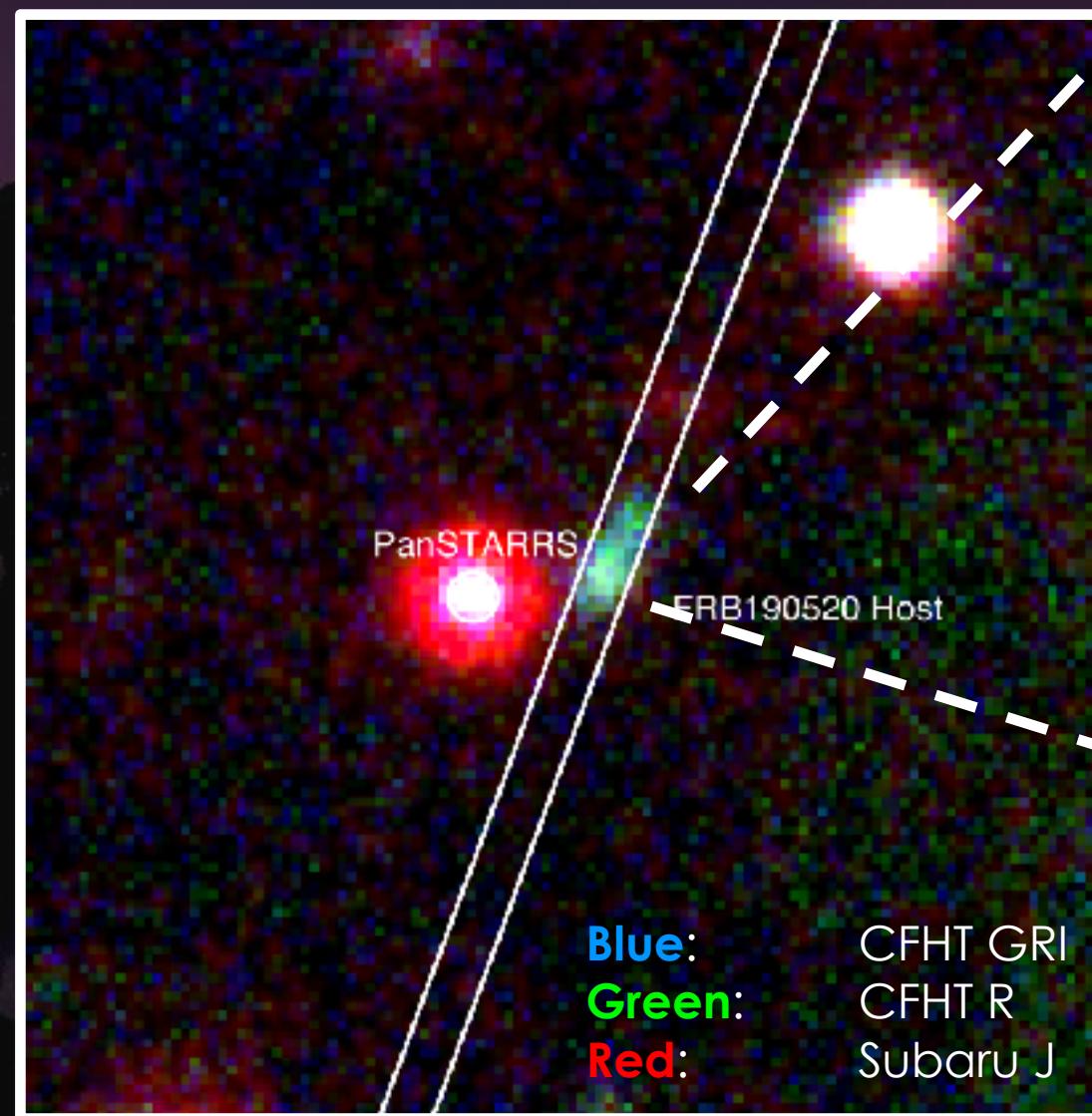


Credit Niu et al. 2022 / Saxton (NRAO)

Host galaxy of FRB 190520

a Star-forming dwarf galaxy

Tsai et al. 2021
In prep.



Analogy: NGC1140
a dwarf irregular galaxy

FRB 190520: the *hipper* and *weirder* brother of 121102

In Review | nature portfolio

"this is a highly significant result and well worthy of publication."

PHYSICAL SCIENCES - ARTICLE

A highly active repeating fast radio burst in a complex local environment

By Li, C.H. Niu, Kahlij Aggarwal, Xian Zhang, Shami Chatterjee, Chao-Wei Tsai, Wenfei Yu, Casey Law, Sarah Burke-Spolaor, James Cordes, Yongkun Zhang, Stella Ocker, Jumpei Yao, P. Wang, Yi Feng, You Niino, Christopher Bochenek, Marilyn Cruces, Liam Connor, Ji-an Jiang, Shi Dai, Rui Luo, Guodong Li, C.C. Miao, J.R. Niu, Reehma Anna-Thomas, Daniel Stern, Welyang Wang, Mao Yuan, Youling Yue, D.J. Zhou, Zhen Yan, Weiwei Zhu, Bing Zhang



BADGES



Prescreen

PEER REVIEW TIMELINE

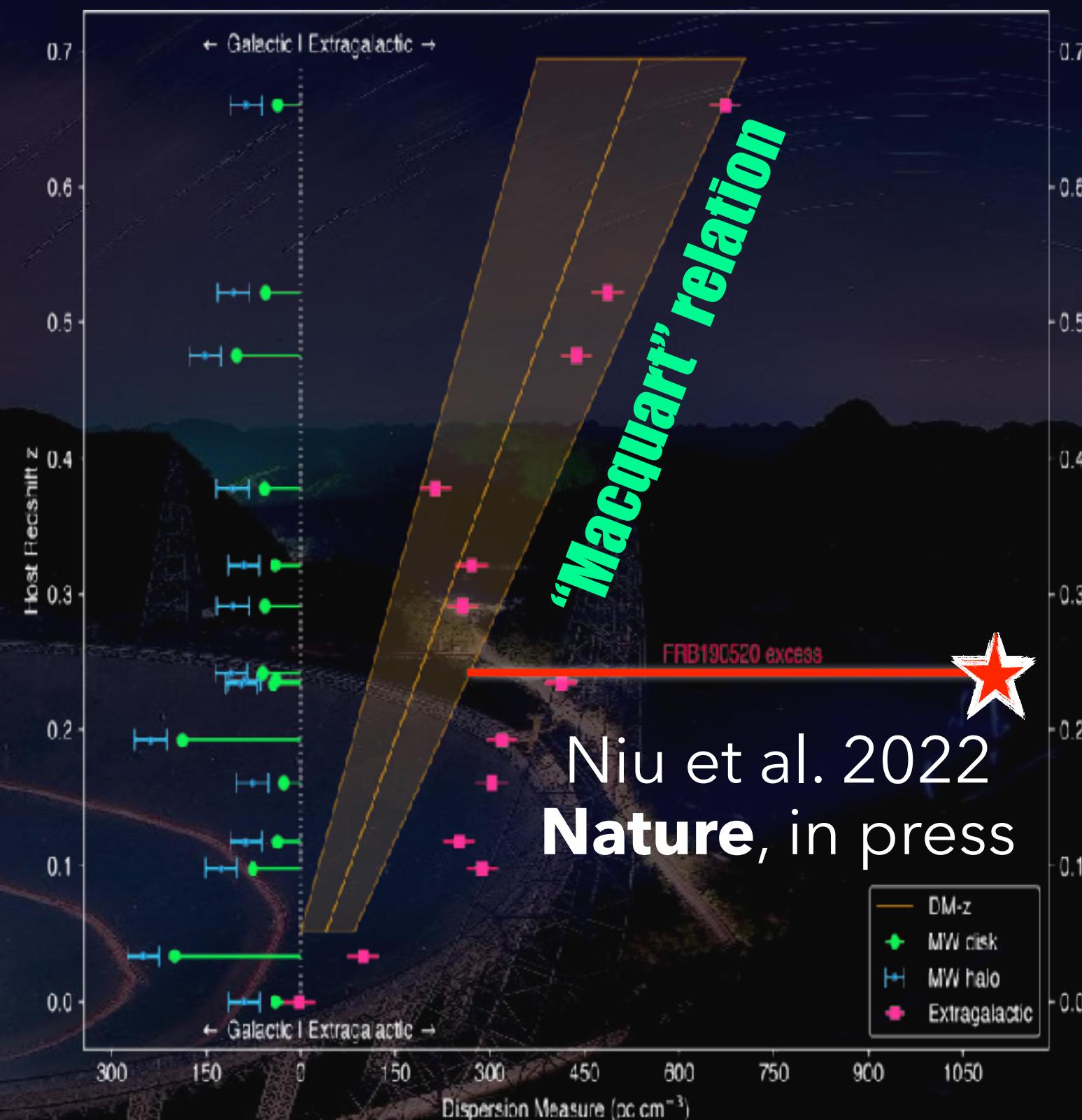
CURRENT STATUS: UNDER REVIEW

Version 1

Posted 28 Jul, 2021

Extraordinary Properties

- ❖ The **highest DM_{host}** ~ 912 pc cm⁻³
- ❖ The **2nd compact PRS** confirmed to co-locate with a FRB
- ❖ **Extreme Activity**: ~300 bursts by FAST, JVLA, Parkes, GBT and VLBA in multiple bands.



"A repeating fast radio burst associated
with a persistent radio source"
Niu et al. 2022 **Nature**



同一个世界观同一片天空：“神兽”仿《故宫图册》

FRB121102 Burst Energy Statistics

$$E \simeq \frac{4\pi D_L^2}{(1+z)} \mathcal{F}_\nu \nu_c \quad (\text{Zhang 2018})$$
$$= (10^{39} \text{ erg}) \frac{4\pi}{(1+z)} \left(\frac{D_L}{10^{28} \text{ cm}} \right)^2 \frac{\mathcal{F}_\nu}{\text{Jy} \cdot \text{ms}} \frac{\nu_c}{\text{GHz}}$$

Cumulative burst energy distribution:

$\beta = -0.7$ JVLA, AO, GBT Law+ 2017

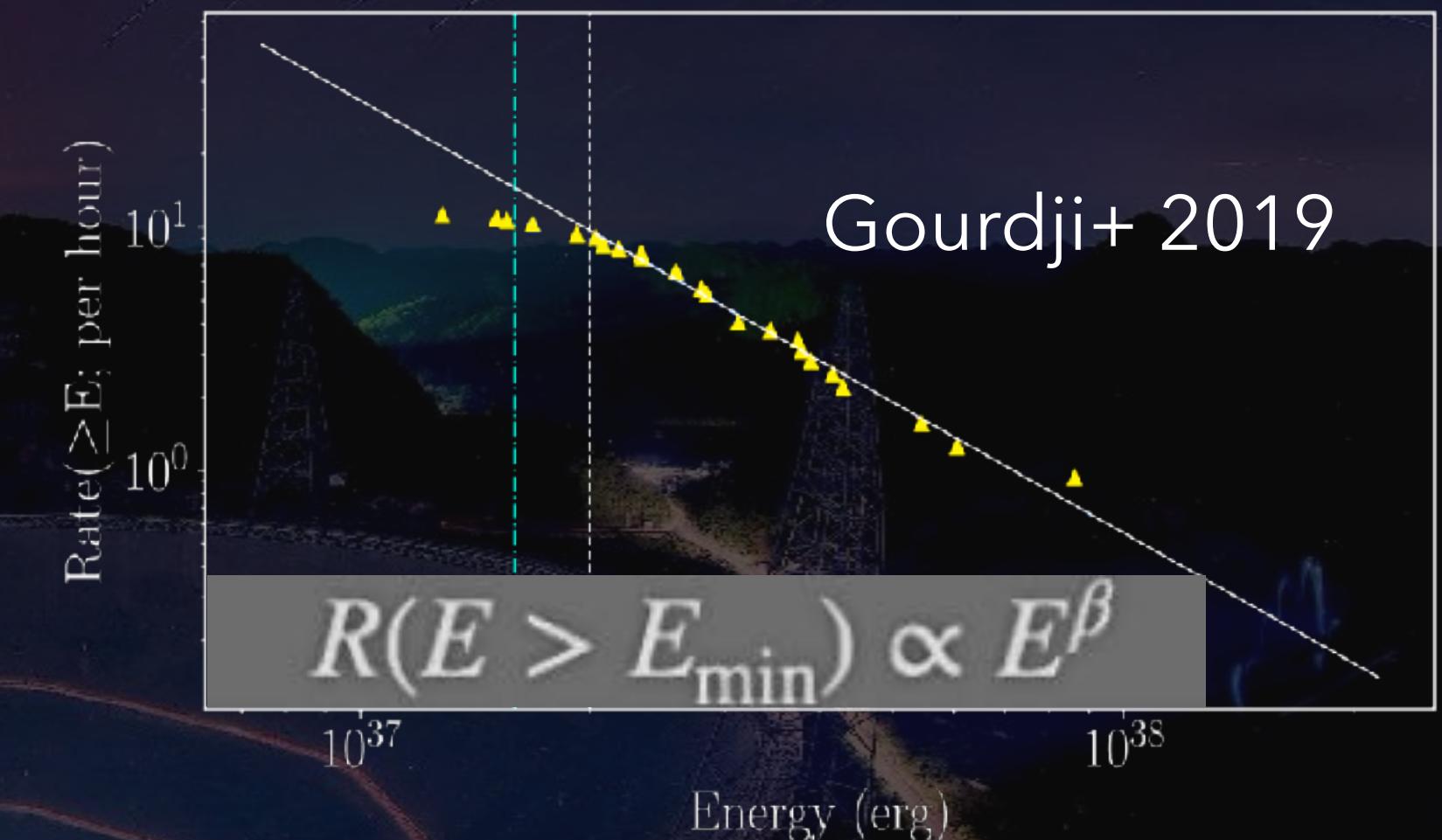
$\beta = -1.8 \pm 0.3$ AO Gourdji+2019

$\beta = -1.2 \pm 0.2$ Effelsberg Cruces+ 2020

FAST L-band 1.25GHz flux calibration

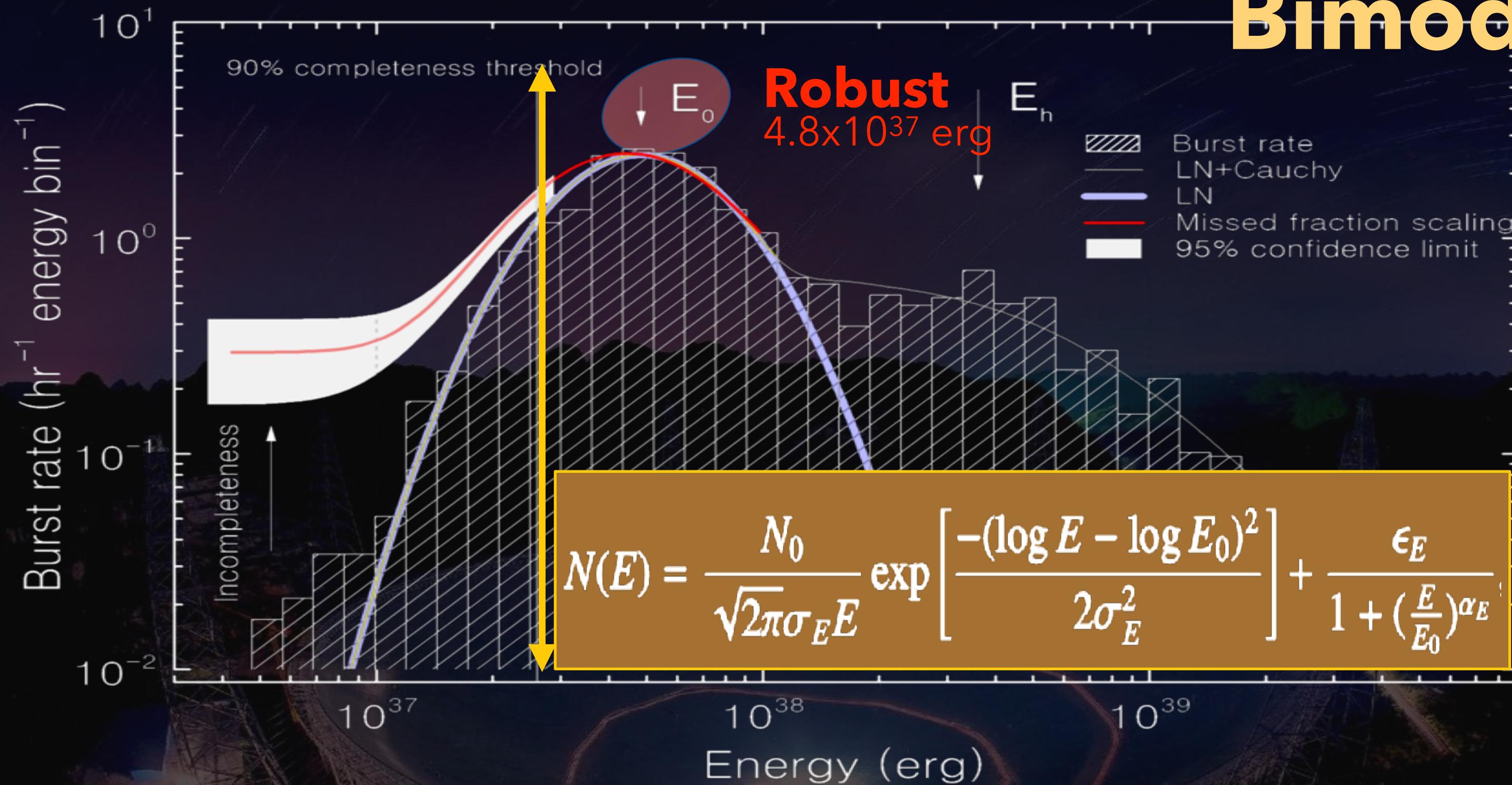
$1\sigma = 2.1 \text{ mJy (1ms)}$ $z=0.193, D_L=949 \text{ Mpc}$, $1 \text{ Jy ms} = 1.07 \times 10^{39} \text{ erg}$

$7\sigma = 15 \text{ mJy}$ $4 \times 10^{36} \text{ erg} < \text{Energy} < 8.0 \times 10^{39} \text{ erg}$



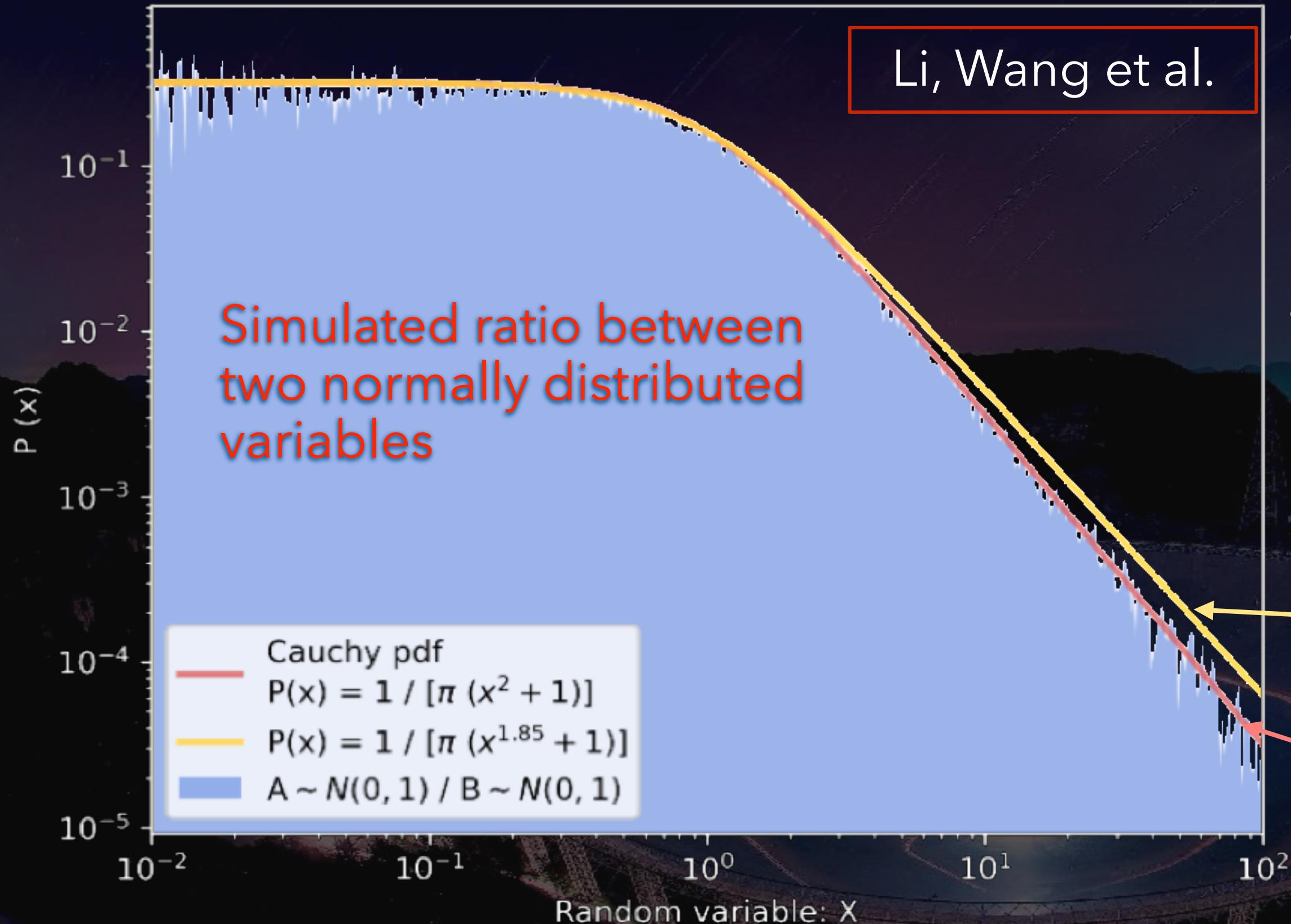
Burst Rate Energy Distribution

Bimodel



A bimodal burst energy distribution of a repeating fast radio burst source
Li, Wang et al. 2021 **Nature**, 598, 267

Burst Rate Energy Distribution - bimodel



- The Lorentz/Cauchy function describe the ratio between two normally distributed variables
- The best-fit index of 1.85 (generalized Cauchy function) is close to 2 within one $\sigma \sim 0.3$

FRB 121102 (2019episode)

- No (quasi)-periodicity between 1ms and 1000s
- Bimodal energy distribution favors stochastic events
- Total energy in ~60 days ~ 38% of a single magnetar's energy

Unlikely an isolated magnetar!

A bimodal burst energy distribution of a repeating fast radio burst source

nature

L. Wang, 2021 DOI: 10.1038/s41586-021-03878-5

CRAFTS webpage: <https://crafts.bao.ac.cn/>

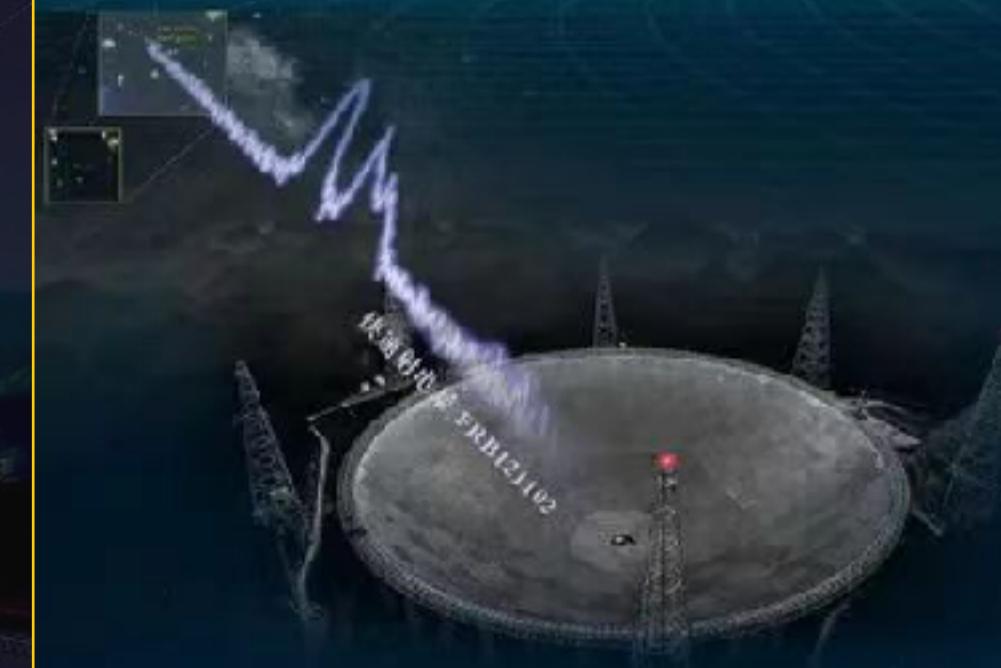


2021年度中国科学十大进展

1. 火星探测天问一号探测器成功着陆火星
2. 中国空间站天和核心舱成功发射、对接
3. 从二氧化碳到淀粉的人工合成
4. 嫦娥五号月球样品揭示月球演化奥秘
5. 揭示SARS-CoV-2逃逸抗病毒药物机制
6. FAST捕获世界最大快速射电暴样本
7. 实现高性能纤维锂离子电池规模化制备
8. 可编程超导处理器“祖冲之号”的量子行走
9. 自供电软机器人成功挑战马里亚纳海沟
10. 揭示鸟类迁徙路线成因和长距离关键基因

FAST

捕获世界最大快速
射电暴样本



该研究首次展现了快速射电暴的完整能谱，
深入揭示了快速射电暴的基础物理机制。

Depolarization of FRB repeaters ?

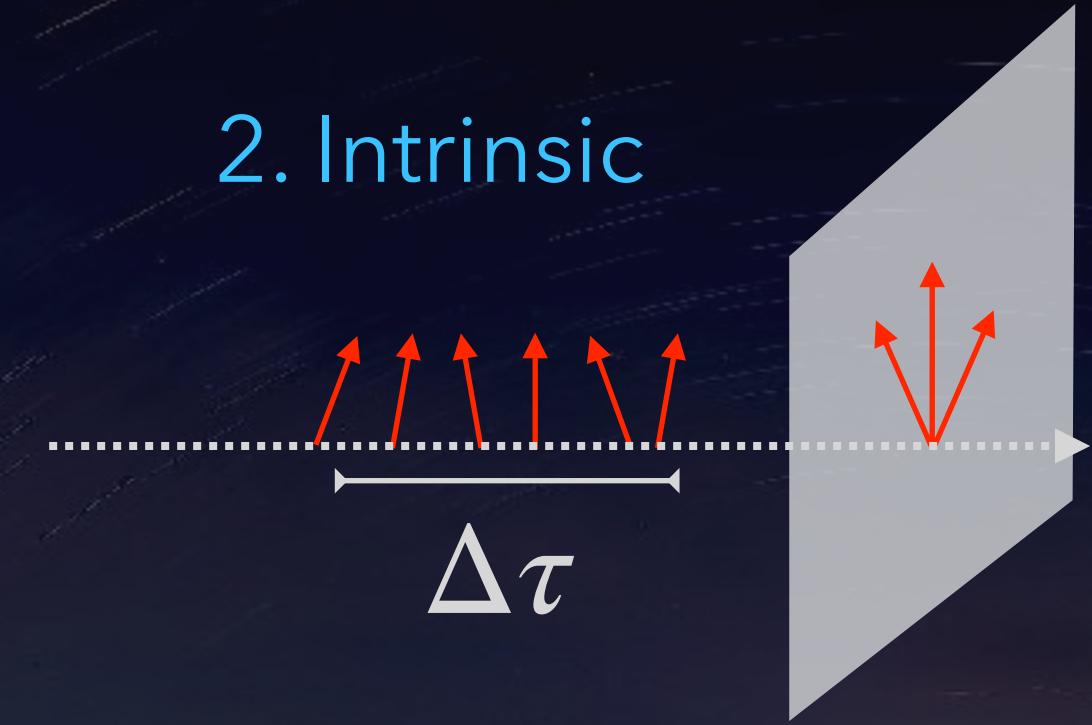
1. Channel smearing



$$f_{dePol} = 1 - \sin(\Delta\theta)/\Delta\theta$$
$$\Delta\theta = \frac{2c^2\Delta\nu RM_{obs}}{\nu_c^3}$$

cf. Faraday rotation

2. Intrinsic



for pulsars, cf. Petrova 2001

3. multi-path propagation

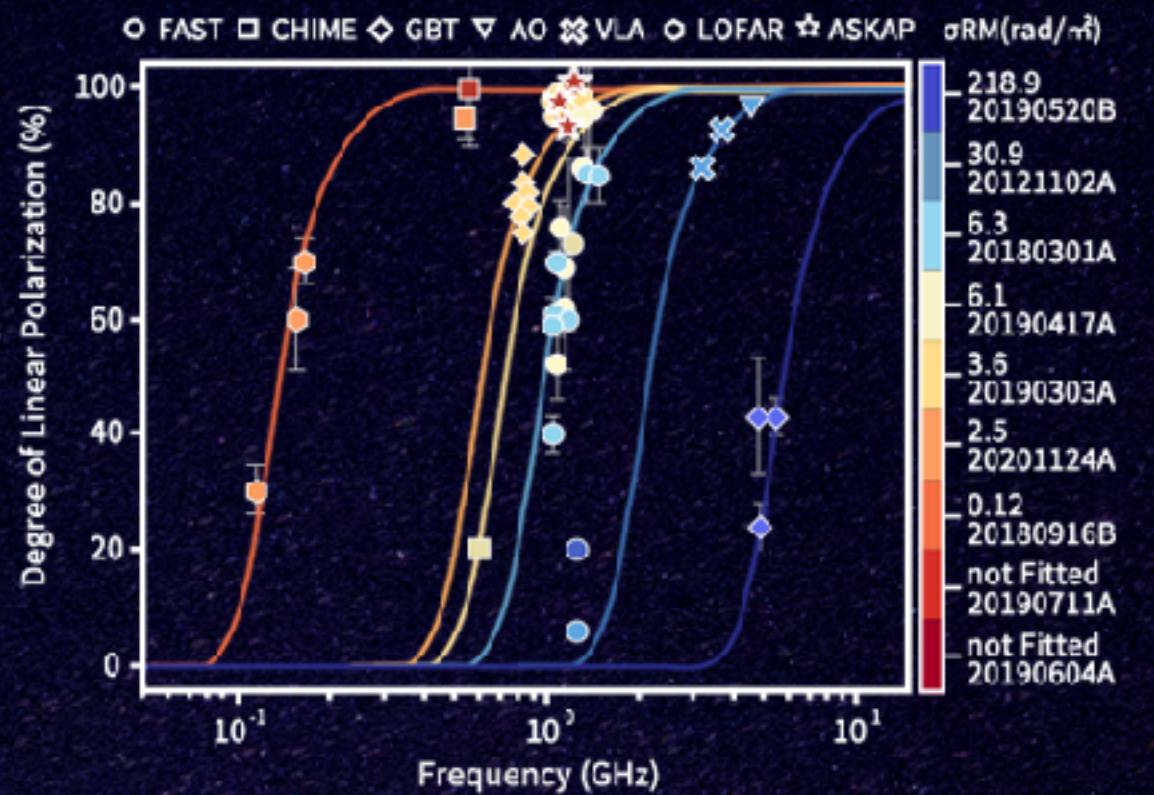


Multi-path propagation through
different RMs

$$f_{dePol} = 1 - \exp(-2\lambda^4 \sigma_{RM}^2)$$

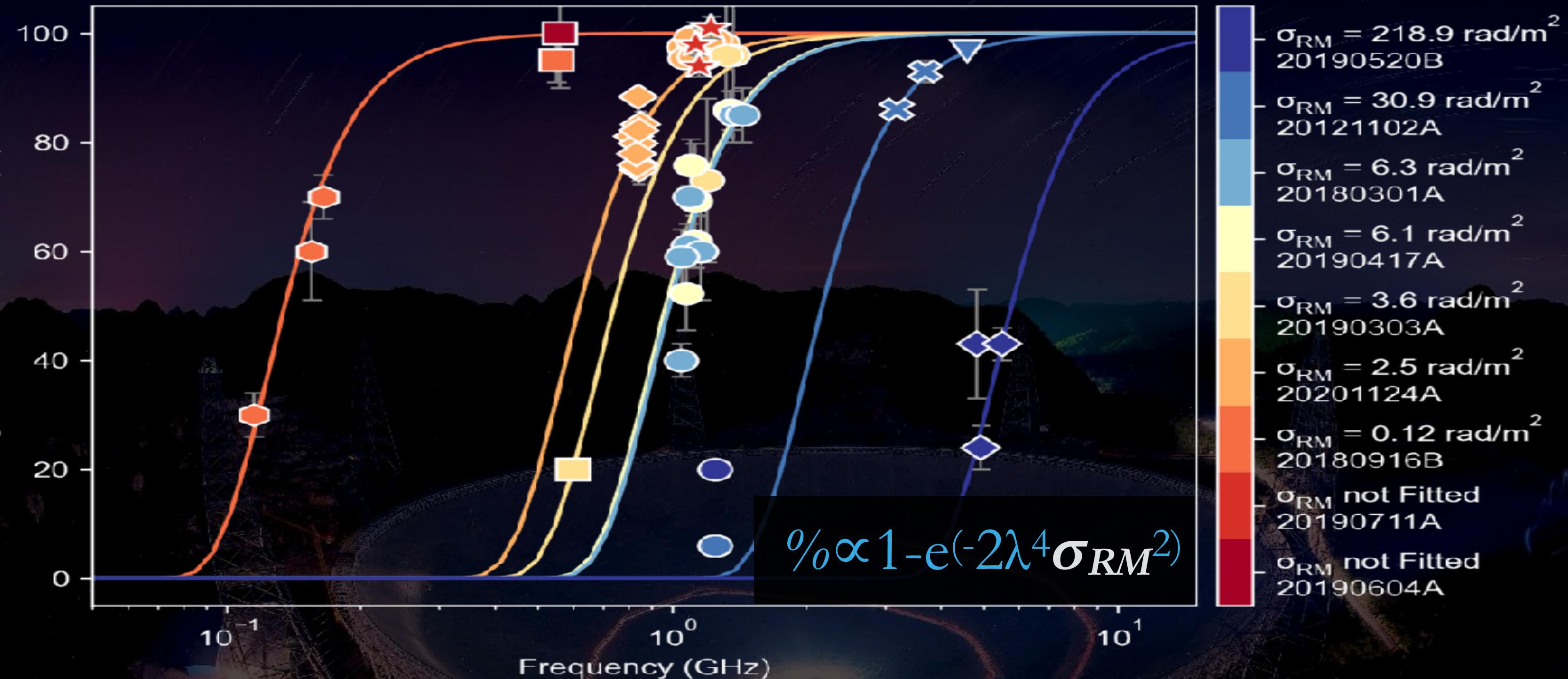
e.g O'Sullivan et al. 2012

A New Unified Characterization of Fast Radio Bursts Reveals Their Origin



Unified characterization of all FRBs - σ_{RM}

○ FAST □ CHIME ◇ GBT ▽ AO × VLA ◆ LOFAR ★ ASKAP



Feng et al. 2022, *Science*, 375, 1266-1270



AO - FAST

Transient Universe



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